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Successful Functional Prototyping with 3D Printing

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SUCCESSFUL FUNCTIONAL PROTOTYPING WITH 3D PRINTING

The goal of the independent study is to develop a training module that educates users on how to successfully incorporate 3D printed parts into functional prototypes. To start, online research was conducted on recommended practices for 3D printing of functional prototypes. During this research, I identified 3D printing visualizations that demonstrated these recommended practices and printed them for use in the module. I also researched other academic makerspaces with respect to their 3D printing capabilities and training provided to users. Then, I performed mechanical tests on 3D printed "dog bone" specimens to characterize the effect of print orientation on the strength and elongation. It was found that the specimens printed in the vertical orientation were significantly weaker than those in the flat and horizontal orientations. This difference based on print orientation is likely due to the vertical specimens' strengths being reliant on layer adhesion rather than infill pattern. These observations held true for the gyroid specimens as well, but the differences between the print bed angle significantly decreased. Additionally, the overall maximum loads significantly increased for all print orientations, which could be attributed to the gyroid infill being much stronger than the grid infill overall. Finally, I surveyed members of our makerspace about their current understanding and experience with 3D printing. The culmination of the research and experimentation resulted in a training module for the Spartan Light Metal Products Makerspace on functional prototyping with 3D printing. The module itself details various information regarding 3D printing terminology, commonly encountered problems, and ways to address these problems. Included in the module are images of 3D printed visual demonstrations that showcase to users what the terminology means and what the printing capabilities of the printers are.

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1 INTRODUCTION

3D printing is the most popular activity in the Spartan Light Metal Products (SLMP) Makerspace at Washington University in St. Louis. Users who 3D print parts for functional prototypes often discover that their parts/assemblies do not work as expected in their design. The goals of this independent study are to create an advanced training module for the SLMP Makerspace for "functional prototyping using 3D printing" that will guide users to more successful prototyping and to recommend improvements to 3D printing options in the SLMP Makerspace. Specific tasks supporting these goals are:

1. Conduct online research synthesizing current "best practices" for 3D printing, including makerspaces at other universities and to identify additional materials and printers to expand functional prototyping at the SLMP Makerspace.

2. Survey current SLMP Makerspace users and instructors on their experiences with 3D printing functional parts. Ask users to review draft versions of the training module and revise based on their feedback.

3. Fabricate and test 3D printed parts and assemblies to investigate the effect of the print orientation and print bed angle on maximum load and tensile strain.

2 3D PRINTING FOR FUNCTIONAL PROTOTYPING: ONLINE RESEARCH

To build a foundation for the functional prototyping with 3D printing training module, online research was conducted to consolidate information already readily available on the internet. The resource referenced was All3DP [3], a website containing a variety of articles regarding all things 3D printing related. From this website, various articles were read and the information from those articles was consolidated into the training module. Additionally, 3D printable visual demonstrations were printed for educational purposes in the SLMP Makerspace. This section summarizes the information from the online research and showcases the visual demonstrations printed.

2.1 Best Practices for Functional Prototyping

The process of 3D printing begins with a design on a computer that is converted to a surface representation, known as an .stl file, to generate a 3D model. These models can be made using computer aided design (CAD) softwares or files can be acquired from online sources, such as UltiMaker Thingiverse[4], a primarily free, open-source website with thousands of user-contributed designs. With generating a CAD file, the user gets to make both design choices when designing the part and choices with regards to 3D printing slicer settings. Comparatively, users obtaining .stl files online only get choices with regards to 3D printing slicer settings.

When looking for resources online, All3DP, a vast resource for 3D printing related articles, was used. The online research was limited to articles related to best 3D printing practices and articles related to functional prototyping. Topics related to best practices for functional prototyping include selection of the method of 3D printing to use, determining what slicing software to use, making material choices, understanding what slicer settings to use, determining how to support a part, and taking into account part interactions, such as clearances and tolerances.

2.1.1 Types of 3D Printing

When 3D printing prototypes, it is important to consider both what method of 3D printing and what material to use. The article, "3D Printing Prototyping - The Ultimate Guide" by All3DP [1], discusses three 3D printing methods: Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS). FDM is a 3D printing process that uses the the process of making physical objects by building up successive layers of material with an extruded thermoplastic filament [2]. SLA is a 3D printing process that uses a light source, either a laser or projector, to cure liquid resin into hardened plastic [3]. SLS is a 3D printing process that uses a high-power laser to sinter small particles of polymer powder into a solid structure based on a 3D model [4]. While all 3D printing methods have their merits, we will be focusing on applications of FDM as it is the primary 3D printing method used for functional prototyping in the SLMP Makerspace.

2.1.2 Slicing Software for FDM 3D Printing

Before being 3D printed, the CAD model of the part must be prepared in a slicer. A slicer is a 3D printing software that prepares a 3D model for a 3D printer by interpreting the CAD file and generating instructions for the 3D printer on how to extrude filament to produce each layer [5].

[3] https://all3dp.com/
[4] https://www.thingiverse.com/

Slicing software incorporates information about the capabilities of a specific printer while allowing the user to adjust parameters that control the speed and quality of the printing process to generate a file known as gcode, the commands to control parts of a 3D printer [6]. The article "Top 20: Best 3D Printer Slicer Software" [5] recommends a variety of software available to use based on experience level and cost. The primary software used by the SLMP Makerspace is 3DPrinterOS [5], a cloud-based 3D printing management program that includes slicing software based on Cura, a popular open-source slicing software [7]. The article specifies that the software is recommended for advanced/professional users with a freemium option. For the SLMP Makerspace, 3DPrinterOS is utilized both as a slicing software for users, for free, and as a print management system. Makerspace users can also use slicing software provided by 3D printer manufacturers that are optimized for those printers then submit gcode directly to 3DPrinterOS

2.1.3 Material Choices for FDM 3D Printing

The article on types of 3D printing [1] also discusses material choices. These choices vary based on the application of the 3D printing part and the method of 3D printing used. The basics of the 3D printing materials mentioned in the article are summarized in Fig. 1

Property	Materials	Cost	3D Printing Technology*
Hard	PLA	Cheap	FDM, SLA
Flexible	TPU, Resin	Affordable	FDM, SLS
Clear	Resin	Affordable	SLA
Durable	Nylon, Carbon Fiber	Moderate	FDM, SLS
Sustainable	Recycled PETG, Recycled PLA	Affordable	FDM
Heat Resistant	Flame Resistant PLA	Affordable	FDM, SLS
Soft-Touch	TPU, Flexible Resin	Moderate	FDM, SLA

Figure 1: Chart summarizing the basics of 3D printing materials from the 3D Printing Prototyping article [1].

The SLMP Makerspace currently has PLA, rPLA, PETG, rPETG, TPU 85A, and TPU 95A available to users for FDM printing, but 3DPrinterOS has the slicing capabilities for even more materials.

2.1.4 Slicer Settings for FDM 3D Printing

Infill is the pattern that is printed inside of a solid portion of 3D printed part [8]. It can reduce weight and print time while supporting the outside of the part and varies from 0% to 100%. 3D printing softwares provide 14 types of infill available for use, each with their own benefits. The article "Cura Guide to the Best Infill Patterns" [9], recommends infill patterns, available in Cura Slicer 5.3, for four main categories of printing types:

[5] https://www.3dprinteros.com/

- Models and Figurines (Lightning, Lines, Zig-Zag): Typically the fastest infill pattern to print and can be used for some prototyping parts.
- "Standard" 3D Prints (Grid, Triangles, Tri-Hexagon): Ideal for prints subjected to low stress.
- Functional 3D Prints (Cubic, Cubic Subdivision, Octet, Quarter Cubic, Gyroid): Used in functional 3D prints that require high strength in multiple directions.
- Flexible 3D Prints (Concentric, Cross, Cross 3D): Infill patterns used with flexible filament to preserve the flexible nature of the print,

Additional settings to consider are scale and wall thickness. Shown in Fig. 3d and 3b are 3D printed visual demonstrations for scale and wall thickness respectively. Scaling is important to consider when preparing a part for print because of the way print quality can be affected. The visual demonstration in Fig. 3b shows what wall thicknesses are able to be printed with the SLMP Makerspace Prusa printers that have a nozzle size of 0.4 mm. It can be seen that the thinnest wall that could be printed was 0.5 mm. This, in combination with scaling, shows the user the limitations of printing smaller objects.

2.1.5 Supports

With the layer-by-layer method of FDM, there comes some difficulties when printing complex features of a part, such as overhangs or bridges. In general, overhangs and bridges are parts that are not supported by anything from below, according to the article "3D Printing Supports – The Ultimate Guide" [10]. To distinguish between the two, an overhang is any unsupported part while a bridge is an unsupported part that spans across a gap. Shown below in Fig. 2 are visual examples of these features.

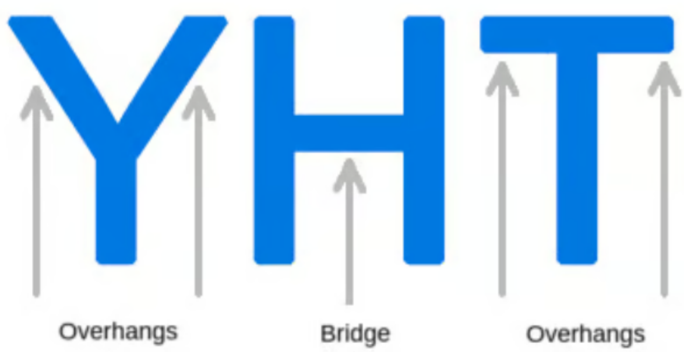


Figure 2: Image of overhangs and bridges using the letters "Y," "H," and "T" [10].

The article mentions the 45 degree rule for overhangs which states that "if an overhang tilts at an angle less than 45 degrees from the vertical, then you may be able to print that overhang without using supports" [10]. A visual demonstration of overhangs at various angles is shown in Fig. 3c. For bridges, the article mentions the 10 mm rule that states that "if a bridge is less than 10 mm in length, the printer may be able to print it without supports" [10]. A visual demonstration of bridging from 15 mm to 110 mm is shown in Fig. 3a.

2.1.6 Tolerances for Assembling 3D Printed Parts

The article "3D Printing Holes: 5 Simple Tips" [11] discusses best-practices when 3D printing holes. These best-practices include calibration of the printer to ensure the machine is as precise as possible, not printing mid-air by either breaking up a print or by "filling in" holes with two layers of plastic to support the hole from the bottom, and being aware of overhangs by altering holes to be teardrop-shaped instead. While the SLMP Makerspace does not regularly calibrate printers, the other best-practices can be implemented into the functional prototyping with 3D printing training module with regards to designing the CAD file for 3D printing. Additionally, other considerations the article brings up is about how the holes will be interacting with other parts, including tightening/compliant mechanisms, which are methods to make sure you have holes that wrap tightly around an object, and tackle threads, which is the creation of higher quality threaded holes using a lower layer height. A visual demonstration showcasing how various tolerances fit together is shown in Fig. 3e. This visual demonstration includes a 10 mm x 10 mm peg that can be inserted into square holes where the squre holes are printed with sides that are nominally 10.25 mm to 10.45 mm. This demonstration showcases the interaction of parts based on the amount of tolerance in the square holes.

2.1.7 Clearances for Multiple Parts Printed Together

Tolerances with parts and how the parts will interact based on the type of interference is covered in the article "3D Printing Tolerances: How to Test & Improve Them" [12]. It discusses clearance fit, a fit where the shaft diameter is significantly narrower than the hole diameter, interference fit, where the shaft diameter is the same as or slightly wider than the hole's diameter, and transition fit, where the shaft diameter is slightly smaller than that of the hole. When assembling 3D printed parts with these fits, there could be some difficulties encountered with the connection not fitting as intended. Through the use of a clearance test print, as seen in Fig. 3f, the clearance capabilities of a 3D printer can be tested, and the user can determine which amount of clearance between a cylinder and a hole allows the cylinder to rotate. The article also briefly discusses potential sources of error, including calibration of the printer, errors in the software, and design errors.

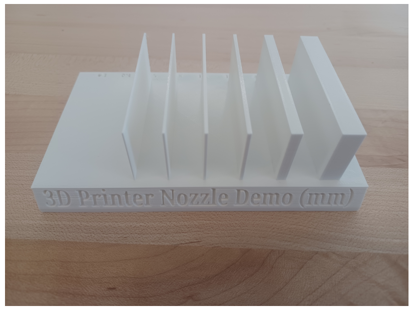
2.2 Summary of Best Practices Learned from Online Research

The articles read discussed best practices for 3D printing, including the inclusion of supports to make sure overhangs and bridges would be able to be printed, adjusting holes to be a teardrop shape to avoid bridging when printing holes, and adjusting properties of the file, either in the CAD file itself or with the slicing software, to suit the parts' purpose. These properties would include selections in the slicing software, such as the type of material selected for printing the part, the infill pattern used based on the purpose of the print, and the number of shells used to increase durability. In the functional prototyping-related articles, topics included things to take into account when 3D printing for functional prototyping, including shrinkage of material when cooling filament, taking into consideration different tolerances based on the type of interaction you would like your parts to have in CAD files, and keeping scaling in mind for all interacting components. From the research done into articles provided by All3DP, the most important factors to take into account when 3D printing for functional prototyping are the nuances in tolerancing in design, the material selected for a part, and the slicer settings for 3D printing.

2.3 Physical 3D Printing Visualizations

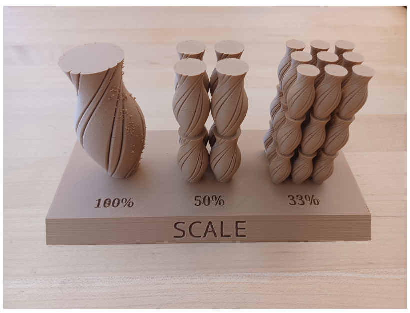
Visual demonstrations were printed using PLA with a 0.2 mm slicing profile and placed around the SLMP Makerspace to showcase the various terms encountered in 3D printing. Included on the base of each visual demonstration is a short description of the part so that is it a standalone item that someone can pick up, read the description, and have some understanding of the purpose of the demonstration print. Also on the base is a QR code that links to the training module if users are interested in learning more. Additionally, links to the original sources of the files for the visual demonstrations were credited on the part as well. The visual models can be shown below in Fig. 3:

(a) Bridging[6]visual demonstration.

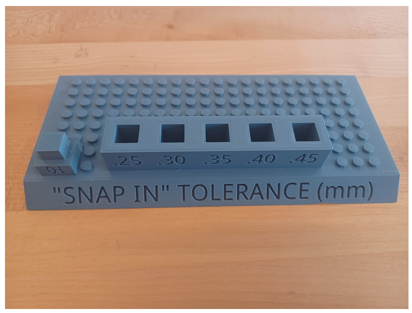


(b) Nozzle visual demonstration.[7]

(c) Overhang[8]visual demonstration.



(d) Scale[9]visual demonstration.



(e) Snap fit[10]visual demonstration.

(f) Clearance[11]visual demonstration.

Figure 3: 3D printing visual demonstrations.

[5]https://www.thingiverse.com/thing:2512390
[6]This visual demonstration was designed and printed by the SLMP Makerspace.
[7]https://www.thingiverse.com/thing:2512390
[8]https://www.thingiverse.com/thing:3645106
[9]https://www.thingiverse.com/thing:365081
[10]https://www.printables.com/model/116911-clearance-tolerance-test/comments/583357

3 SURVEY OF 3D PRINTING AT OTHER ACADEMIC MAKERSPACES

In order to understand how the SLMP Makerspace can improve, it is useful to research how other academic makerspaces have successfully implemented 3D printing for functional prototyping. This section summarizes the research done into various academic makerspaces and how our makerspace compares to them. Additionally, this section details responses from a survey conducted for people who have used the 3D printing services offered by the SLMP Makerspace.

3.1 Comparison of Academic Makerspace Capabilities

A makerspace is defined as a collaborative space where people can innovate [13]. In this case, university-level academic makerspaces that support rapid prototyping and 3D printing are being researched. When looking into the specific university makerspace(s), the criteria used were:

- Do they have 3D printers available for use in the space?
- Do they have resources for functional prototyping?
- Do they support functional prototyping with 3D printing?

Using these criteria, 26 makerspaces from 15 institutions, including the SLMP Makerspace, were selected for comparison, as listed in Appendix C. Once the list of makerspaces was established, specific attributes to look into were defined below:

- Courses for Functional Prototyping: Are courses offered in the space, featured by the space, or offered in conjunction, whether as training, additional resources, etc.?
- Functional Prototyping Resources: Does the space promote or emphasize functional prototyping by featuring additional resources for functional prototyping, showcasing functional prototyping projects, etc.?
- Industrial 3D Printers: Does the space have industrial-level[12] 3D printers?
- 3D Printing In-Person Training: Is in-person training offered for users for the 3D printers?
- 3D Printing Online Training: Is online training offered for users for the 3D printers?
- Self-serve/Hybrid 3D Printing: Are there 3D printers that people can access directly/without staff?
- Workshops for 3D Printing: Are there workshops offered in these spaces for 3D Printing?

[12]Industrial printers are printers that are designed to work in harsh environments, including printing with high-performance and engineering-grade materials, having capabilities for large print volumes, and delivering repeatable and reproducible performance [14].

3.2 Makerspace Comparison

Table 1 below shows a summary chart of the makerspaces researched. In the first row of the chart is the SLMP Makerspace to see how we compare to the others. Table 2 shows a summary of the chart, indicating how many of the 26 makerspaces appeared to have each attribute.

Table 1: Makerspace comparison chart.

University	Makerspace	Attributes						
		Courses for Functional Prototyping	Functional Prototyping Resources	Industrial 3D Printers	3D Printing In-Person Training	3D Printing Online Training	Self-Serve/ Hybrid 3D Printing	Workshops for 3D Printing
Washington University in St. Louis	SLMP	✓	X	X	X	✓	X	✓
University of Wisconsin - Madison	UW Makerspace	✓	✓	✓	X	✓	X	✓
Harvard	REEF	X	✓	X	✓	X	X	X
	SC Fabrication Lab	X	X	X	X	X	X	✓
Princeton	PUL Makerspace	X	X	X	✓	✓	X	X
	Keller Center Makerspace	✓	X	X	✓	✓	X	X
	StudioLab	X	X	X	✓	✓	X	✓
Duke	Lilly Library	X	X	✓	X	✓	X	✓
Yale	Center for Engineering Innovation & Design	✓	X	✓	X	✓	✓	X
UC Berkeley	Supernode	X	X	X	✓	✓	X	X
	Jacobs Institute for Design Innovation	X	X	✓	✓	✓	X	✓
	CITRIS Invention Lab	✓	X	X	✓	✓	X	X
Georgia Tech	The Flowers Invention Studio	X	X	X	X	X	X	✓
	The Yang Aero Maker Space	X	X	✓	✓	X	X	X
	The BME Design Shop	X	X	✓	X	X	X	X
	The MILL	X	X	✓	X	X	X	X
Stanford	create:space	X	X	X	✓	X	X	✓
	GSE Makery	X	X	X	X	X	X	X
	lab64	X	✓	X	✓	✓	X	✓
Rice	oedk	X	X	X	X	✓	X	✓
MIT	Makerworkshop	✓	✓	✓	✓	✓	X	X
University of Washington – Seattle	The MILL	X	X	X	X	✓	X	✓
	GIX Prototyping Labs	X	✓	✓	X	X	X	X
Case Western	think[box]	X	✓	✓	X	✓	X	✓
NYU	Makerspace	X	✓	✓	✓	✓	✓	✓
Carnegie Mellon	TechSpark	X	X	✓	X	✓	X	X

Table 2: Summary of attributes for makerspace comparison chart.

Number of Universities per Attribute						
Courses for Functional Prototyping	Functional Prototyping Resources	Industrial 3D Printers	3D Printing In-Person Training	3D Printing Online Training	Self-Serve/ Hybrid 3D Printing	Workshops for 3D Printing
6	7	12	12	17	2	13

It can be seen that the emphasis on functional prototyping varies between universities with no one attribute being consistent among all 26 academic makerspaces. However, it can be seen that the most common attribute among the academic makerspaces is the inclusion of online training for 3D printing followed by the presence of workshops for 3D printing. With regards to how the SLMP Makerspace is doing on functional prototyping in comparison to other academic makerspaces, while we have about 3 of the attributes listed, there are quite a few we are lacking, especially in comparison to the UW Makerspace, which has 5 of the 7 listed attributes. There is still much room for improvement for the SLMP Makerspace, especially with regards to functional prototyping, but, with this independent study, the SLMP Makerspace will have functional prototyping resources available for members through the development of a training module.

3.3 Survey of 3D Printing Users at the SLMP Makerspace

In addition to research into other academic makerspaces, a survey was distributed to users of the SLMP Makerspace who have extensively utilized the 3D printing services. The survey, shown in Appendix D, was used to supplement research into the future training module for functional prototyping with 3D printing. Over the course of the Fall 2023 semester, the survey had a total of 14 respondents. Shown below in Fig. 4 is the distribution of the characteristics of the respondents.

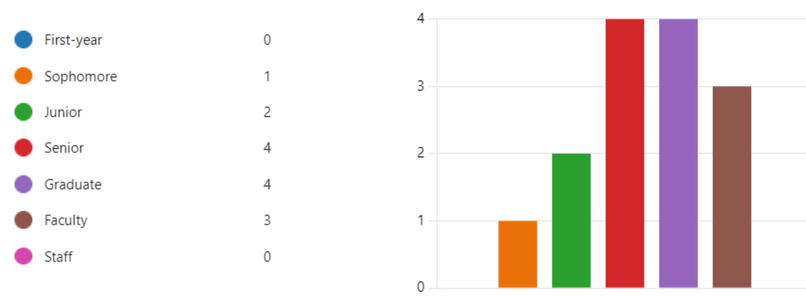


Figure 4: Demographics of users that responded to the SLMP Makerspace 3D printing survey.

The majority of respondents have been members of the SLMP Makerspace for 4 or more years. Additionally, the majority of respondents often used the SLMP Makerspace either daily or weekly and tended to use it for personal purposes followed by course purposes. When asked about the equipment they have used, all the users indicated that they have used the 3D Printer (Prusa). Shown below in Fig. 5 is the complete distribution of equipment usage.

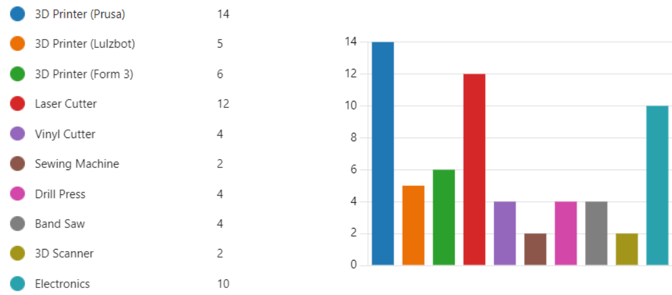


Figure 5: Frequency of equipment users have indicated using in the makerspace.

When asked about what kind of information would be useful in the "Functional Prototyping with 3D Printers" training module, responses included:

- "Details that help a print succeed or commonly fail. Tips about printing/scaling parts that will interact."
- "The effect of print direction on strength Nominal vs. actual thickness of printed walls... multiples of print bed thickness (i.e., usually 0.4 mm) Infill percentage vs. strength Making holes and stuff with overhang without needing support material (steepness < 45 degrees)"
- "It would be helpful to know what infill percentage, infill pattern, and wall thickness to use for a given pressure or force. Advice on how to properly account for part tolerances, or basic estimations for how much larger a 3D-printed part is, would be helpful. "

From the responses to this question, the topics of the training module were tailored to be able to address the topics mentioned in the responses. With regards to feedback for improvements to 3D printing in the SLMP Makerspace, some samples responses were:

- "Dual extrusion. More material options. Another printer option, maybe for specific project uses?"
- "A metal 3D printer would blow my mind. I have seen videos of 3D prints with print support material in very organic/strange shapes that don't intersect with the actual part. I'm not sure if this is a setting or a new software, but that would make removing support material easier. Multiple colors would be so fun for personal projects. Maybe also ways to finish 3D printed parts like sanding, gluing, and priming for paint."
- "It would be nice to have the option be trained to run our own prints. It would also be helpful to have certain printers dedicated to course work."

From the survey as a whole, it seems that users would like the SLMP Makerspace to have 3D printers dedicated to specific purposes, such as being solely for course work. Additionally, having the SLMP Makerspace expand its offerings with regards to 3D printing capabilities, such as dual extrusion, metal, and dissolvable supports, seems to be a common interest among respondents.

4 MECHANICAL CHARACTERIZATION OF 3D PRINTED SPECIMENS

4.1 Introduction

Positioning and orientation of 3D printed parts can affect their strength due to factors such as layer separation and infill location. In order to investigate how these factors might affect 3D printed parts produced in the SLMP Makerspace, I performed uniaxial tensile testing on "dog bone" shaped 3D printed material, similar in shape to those used for tensile testing of metals. This specific shape was chosen because it was easy to print and easy to replicate. This would guarantee consistency between specimens and not take an extensive amount of time to print multiple specimens. Additionally, the "dog bone" shape allowed for the use of an extensometer, allowing much more precise data collection for tensile strain. Figure 6 shows the dimensions of the "dog bone" specimen.

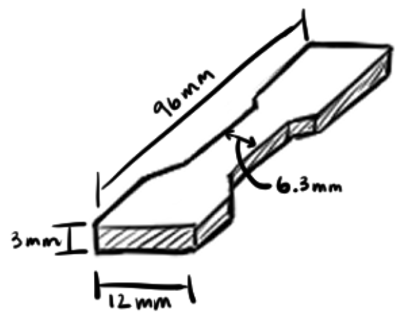


Figure 6: "Dog bone" with dimensions.

A distinction is made in regards to terms used for describing the "dog bones." An individual "dog bone" can be called a specimen, a single material used for testing, while a group of these specimens, whose properties are studied and compared to gain statistical or quality assurance information, is defined as a sample, according to the Instron glossary [15].

4.2 Specimen Printing

All samples were prepared for printing using the slicing software in 3DprinterOS. Slicer settings such as number of shells, number of top and bottom layers, infill type and infill percentage were kept the same for all samples. These samples were printed on an original Prusa i3 MK3 S+ using recycled PLA filament (rPLA). The original Prusa i3 MK3S+ uses FDM, which means that each layer is printed by motion in the X and Y directions, and motion in the Z direction defines the print layers. Figure 7 shows a labelled 3D printer with axes.

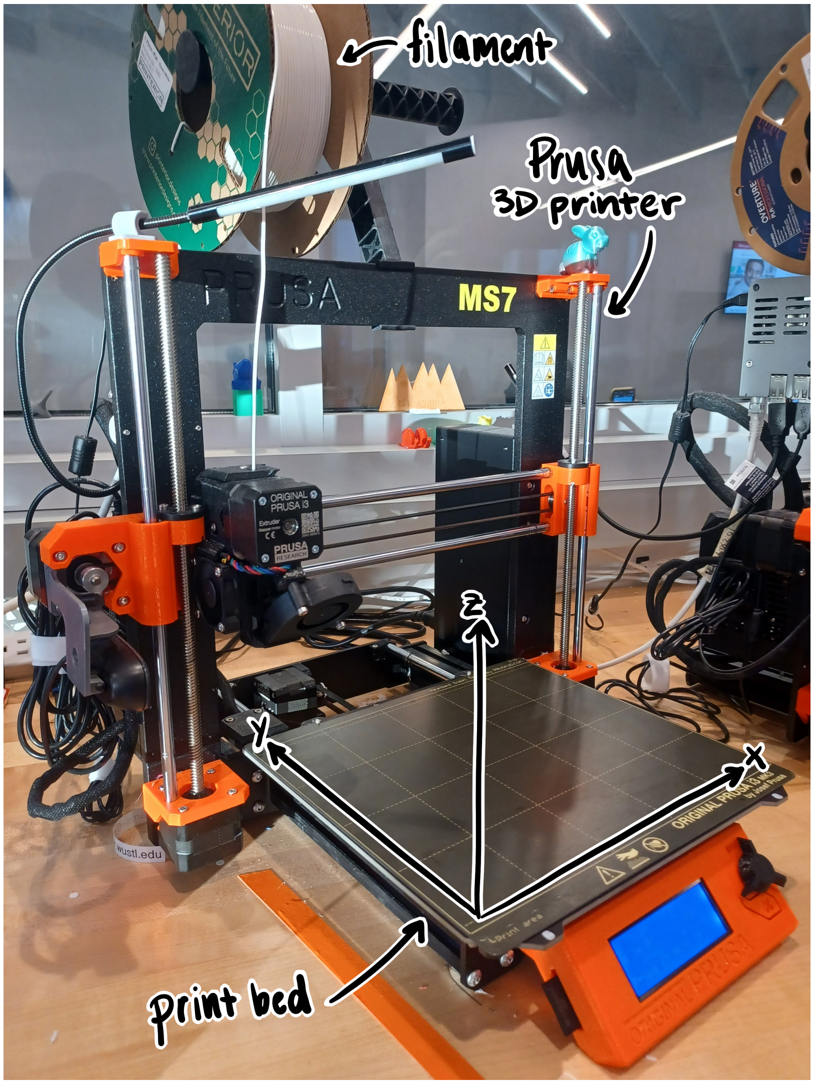
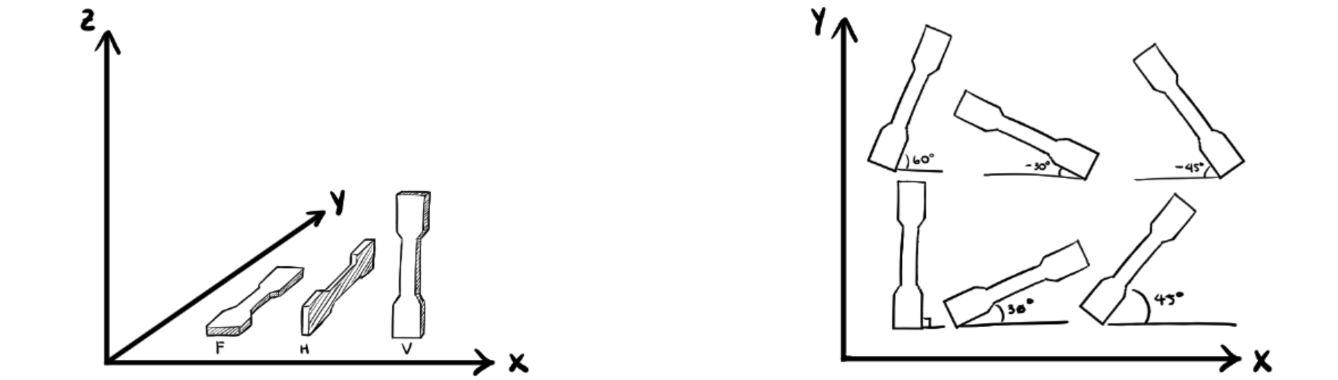


Figure 7: Labelled image of a Prusa i3 MK3S+ used in the SLMP Makerspace.

"Dog bone" specimens were printed in various print orientations with multiple print bed angles. Print orientation is defined as the position of the specimens' print layers on the print bed. Print bed angle is defined as the degree at which the specimen is rotated with respect to a specific axis. A visualization of various print orientations and of the various print bed angles can be seen below in Fig. 8.



(a) Plot of the "dog bone" specimens in their respective print orientations.

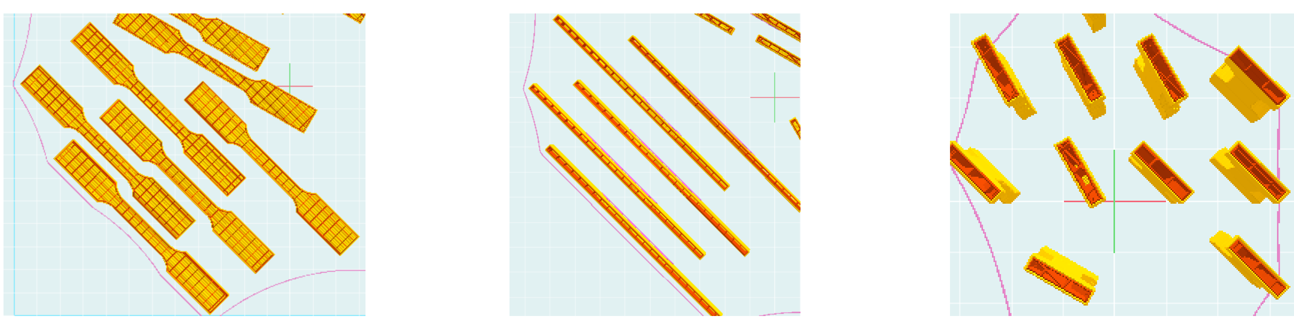
(b) Plot of the "dog bone" specimens in sample print bed angles.

Figure 8: Visualizations of specimen terms.

4.3 Methods

4.3.1 Slicing Software Specimen Preparation

Shown below in Fig. 9 are screenshots from 3DprinterOS cloud slicing modules that show how the specimens were oriented for the grid infill pattern. A grid infill pattern is a square "grid" pattern made of perpendicular lines. This infill pattern was initially chosen to be tested because the grid infill pattern is one of the predefined 3DPrinterOS slicing profiles. The JSON of the 3DPrinterOS slicing profile used is attached in Appendix E.



(a) Flat specimens' grid infill.

(b) Horizontal specimens' grid infill.

(c) Vertical specimens' grid infill.

Figure 9: Infill of grid specimens in 3DPrinterOS.

It can be seen that the infill patterns vary for each specimen based on the specimen's location on the print bed. The grid pattern is always at a 45 degree angle to the X axis, so the angle of the infill relative to the specimen "axes" depends on the print bed angle. The number of grids repeats depending on the infill percentage.

4.3.2 3D Printed Specimen Preparation

The file for the "dog bone" specimen was scaled up to be 3 mm thick, making the overall dimensions 3 mm x 12 mm x 96 mm. The file was then imported into 3DPrinterOS and duplicated so that each print bed angle for each print orientation had 5 specimens, resulting in a total of 40 specimens per print orientation. The flat specimens were printing in batches as they could not fit on one printer bed at the same time. All tested specimens were printed in PLA, the most commonly used material in the SLMP Makerspace. Other printing variables, including percent infill (20%), number of shells (2), and layer height (0.2 mm), were kept consistent throughout the prints. Table 3 below lists the equipment used in preparing and printing the specimens.

Table 3: Apparatus table for specimen printing.

Equipment	Quantity	Description
3D Printer	1	Original Prusa MK3 S+
PLA	--	White PLA (Printerior)
Software	1	3DPrinterOS
Glue Stick	1	Used to adhere prints to build plate
Pliers	1	Used to remove excess material from prints

Glue was applied to the build plate to ensure that there would be sufficient adhesion for the specimens to print. The vertical orientation's specimens required the addition of a brim to print successfully. Once printed, any supports or brims were removed, and specimens were labelled with the material, orientation, degree, and specimen test order (a - e). Figure 10 has images of all the specimens printed in their respective print orientations at the various print bed angles, and Table 4 lists the specimens tested in the experiment.

(a) Specimens printed in the flat orientation and at eight print bed angles after removal from the print bed.

(b) Specimens printed in the horizontal orientation and at eight print bed angles after removal from the print bed.

(c) Specimens printed in the vertical orientation and at eight print bed angles after removal from the print bed.

Figure 10: Print orientations of specimens at the eight print bed angles.

Table 4: Table of specimens.

Specimen		Quantity	Description
Infill	**Orientation**		Grid specimen are printed at angles of –30, -45, -60, 0, 30, 45, 60, and 90 degrees
Grid	FLAT	40	Printed with the largest area on the print bed
	HORIZONTAL	40	Printed with the edge on the print bed
	VERTICAL	40	Printed straight up from the print bed

4.3.3 Mechanical Testing

For the experiment, a universal testing machine was used for tensile testing of the 3D printed specimens. Each specimen was mounted between a set of wedge grips, and the upper wedge grip was connected to 30 kN load cell. A 25 mm extensometer was mounted to the center of the 3D printed specimen, shown in Appendix A. The test software, Instron Bluehill, recorded the distance between the grips, the extensometer strain, and the load cell force at 1 mm/min. Table 5 below provides the table of equipment, while Figure 11 below provides images of the experiment's equipment. A complete schematic diagram of the experimental setup can be found in Appendix A.

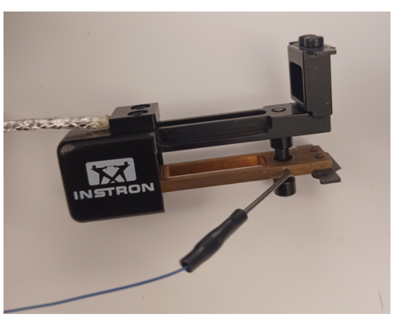
Table 5: Apparatus table for experiment.

Equipment	Quantity	Model Number	Description
Instron	1	68TM-30	Serial #: 000024214
Wedge Grips	2	--	0 – 0.25"
Allen Key	1	--	Tightens the grips
Wedge Grip Lock	2	--	Keeps the grips in place
Load Cell	1	--	30 kN
Extensometer	1	2620-602	25 mm height
Software	1	--	Instron Bluehill


(a) Wedge grips


(b) Control

(c) Load Cell



(d) Extensometer


(e) Allen key


(f) Clamp

Figure 11: Main equipment used in experiment.

Safety glasses were worn at all times in the Shared Instrument Group (SIG) Lab. Attire consisted of close-toed shoes and long pants, and long hair was tied back and jewelry removed. If there were another user in the lab, nitrile gloves and a lab coat were also worn.

To start, the Instron was powered on using the switch on the right side of the machine. Then, after logging into the PC and testing software, the method template was opened. To set up the equipment, wedge grips were attached and secured using a metal connecting rod. Then, they were tightened with an allen key. The extensometer was connected to the machine. Then, the stopper was set at 82.4 cm from the base of the machine. To zero the displacement of the crosshead, the machine was jogged till it hit the stopper, and the initial displacement was zeroed.

To attach the specimen to the machine, it was first clamped by the top wedge grip, ensuring that there was enough area of the specimen exposed to attach the extensometer to. Then, the force reading was zeroed and the bottom of the specimen was clamped in with the bottom wedge grip. Next, the extensometer was attached to the specimen with black dental rubber bands. If there was any pre-load added to the specimen, a note was made in the software. When ready for testing, the safety pin was removed from the extensometer and the strain was zeroed. The machine was then unlocked for testing, and the machine ran till failure. In the event that the displacement reached 2 mm, the extensometer was removed and testing was resumed. Once the testing was done, one rubber band was removed from the extensometer, and the calibration pin was reinserted into the extensometer. The extensometer was then removed from the specimen. Next, the specimen was removed, starting with releasing the bottom clamp and then the top clamp. The crosshead was returned to zero, and any additional post-notes were added to the software. The process was repeated for each specimen.

To analyze the data collected, data were recorded using the Instron Bluehill software, and additional parameters were noted in a Google Sheets document. After testing, the software outputted an Excel spreadsheet with the raw data and a .pdf file summarizing the data obtained. This was generated for each print bed angle for the various print orientations of the specimens tested.

4.3.4 Analysis

The data recorded was exported as .pdf and Excel files for analysis, shown in Appendix B, Tables 6, 7, 8, and 9. Potential sources of error could be due to an inconsistency in data collection. While everything was as consistent as possible, there could have been some deviation in the way the specimens were placed in the machine. In order to minimize this error, the specimens were all tested in the same orientation, being placed in the grips as similarly as possible, shown in Appendix A. Additionally, there were also some minor adjustments made during the test for the extensometer. The first 5 specimen tests for the flat print orientation at the 0 degree print bed angle were done with a 12 mm extensometer, which was later swapped for a 25 mm extensometer. This was to ensure that the data captured would adequately encapsulate the break area.

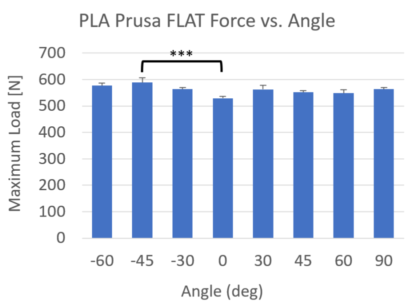
In order to determine significance in the data, 2-way ANOVA tests were performed using the anova2 function in Excel (Microsoft Office 365[13]). The two independent variables were print orientation and print bed angle and the dependent variable tested was either maximum force at failure or extension at failure. Post-hoc tests were performed using the anovan function in the Matlab Statistics toolbox (Mathworks, R2022a[14]).

[13]https://www.microsoft.com/en-us/microsoft-365

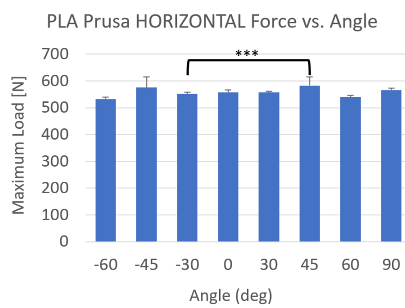
[14]https://www.mathworks.com/products/new_products/release2022a.html

4.4 Results and Discussion

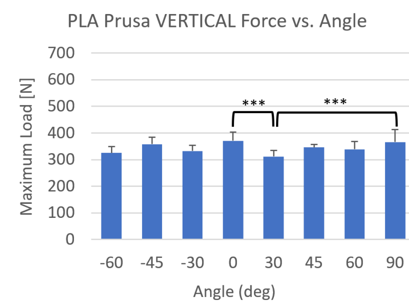
The data collected was consolidated and represented as bar charts. Shown below in Fig. 12 are the bar charts for each print orientation. The mean load at failure is shown in Fig. 12a - 12c for each print bed angle and print orientation. The 2-way ANOVA showed that there were significant differences between print orientations and between some print bed angles. The results of the 2-way ANOVA tests can be seen in Appendix B, Tables 10, 11, and 12. The post-hoc tests showed that the vertical print orientation had a significantly lower failure load than the flat or horizontal print orientations. Within print orientation, the failure load for some print bed angles were significantly different from each other. The print bed angles with significant differences from each other are indicated with a bracket and three stars, which is indicative of a p-value less than 0.001.



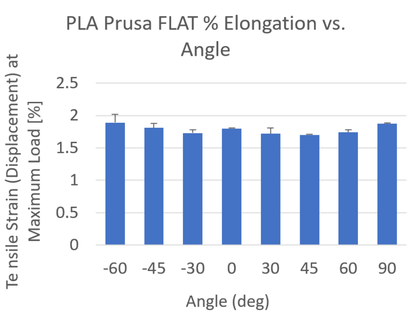
(a) Flat maximum load chart.



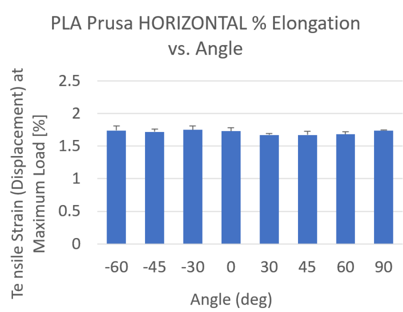
(b) Horizontal maximum load chart.



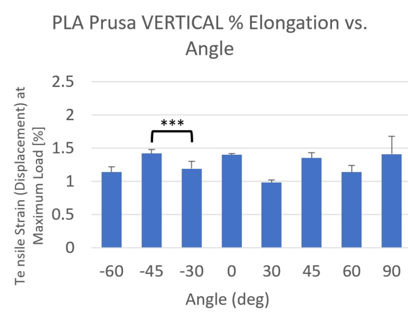
(c) Vertical maximum load chart.



(d) Flat percent elongation chart.



(e) Horizontal percent elongation chart.



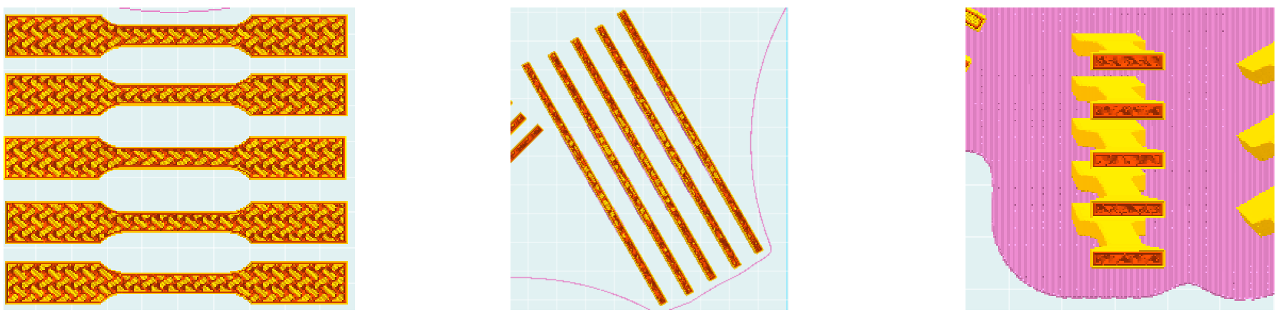
(f) Vertical percent elongation chart.

Figure 12: Grid specimens' bar charts comparing values vs. print bed angle.

It can be seen that there are minimal differences in average maximum loads for the flat and horizontal print orientations. However, there is a significant decrease in the average maximum load for the vertical print orientation. A similar comparison can be made for the percent elongation charts for the print orientations. This difference could likely be due to the flat and horizontal print orientations' strength being based on infill while the vertical print orientation's strength being based on layer adhesion rather than infill.

For the flat specimens' maximum load chart, there is a significant difference in the specimens printed at 0 degrees and -45 degrees, with the 0 degree specimen having the lowest average maximum load while the -45 degree specimen had the highest average maximum load. A similar difference can be seen with the horizontal specimens' maximum load chart with both the -30 and 45 degree specimens orientations. With the vertical specimens, a significant difference can be seen between the 0 degree and 30 degree specimens and the 30 degree and 90 degree specimens. For all of the print orientations' percent elongation charts, there were no significant differences between any print bed angles besides the -45 and -30 degrees for the vertical print orientation.

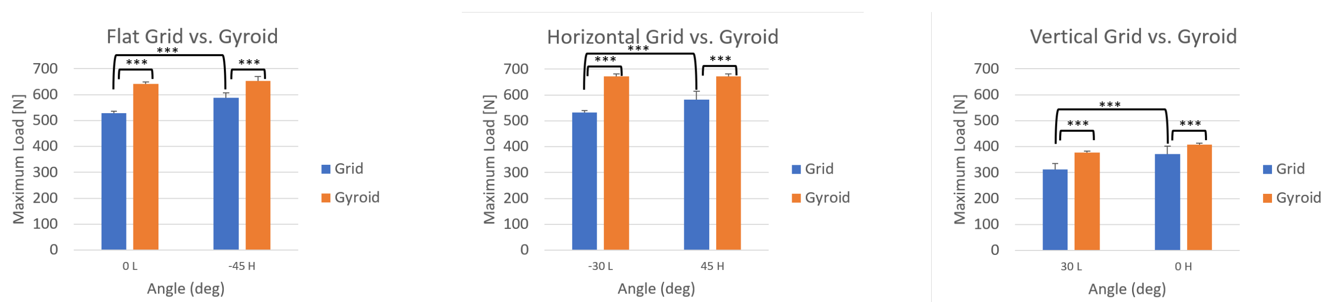
The significant difference between print bed angles for the flat and horizontal orientations were unexpected. Since users may orient parts at different print bed angles to fit multiple parts on the print bed, the SLMP Makerspace would like to minimize these differences. To test whether the type of infill pattern, mentioned in section 2.1.4, would affect the variation in maximum load between print bed angles, the aforementioned angles with significant differences in maximum load were then printed with gyroid infill, an infinitely connected triply periodic minimal surface [16], to determine the effect the change in infill pattern would have on the maximum loads. The 3DPrinterOS infill patterns generated can be seen below in Fig. 13.



(a) Flat specimens' gyroid infill. (b) Horizontal specimens' gyroid infill. (c) Vertical specimens' gyroid infill.

Figure 13: Infill of gyroid specimens in 3DPrinterOS.

All other print parameters remained the same as the grid infill specimens. Then, these specimens were tested using the same procedures as for the grid infill. The gyroid specimens were also analyzed using 2-way ANOVA and post-hoc tests. The summary of the ANOVA results for the gyroid specimens can be seen in Appendix B, Tables 13, 14, and 15. Figure 14 shows the comparison between the two infill patterns' maximum loads. A significant difference is noted with a bracket and three stars, indicative of a p-value less than 0.001



(a) Flat maximum load grid vs. gyroid infill chart. (b) Horizontal maximum load grid vs. gyroid infill chart. (c) Vertical maximum load grid vs. gyroid infill chart.

Figure 14: Maximum load bar charts of grid vs. gyroid infill for the specified print bed angles of the respective print orientations.

The gyroid specimens of all print orientations and print bed angles had a significant increase in maximum loads compared to their respective grid specimens, supporting the notion the gyroid infill is much stronger than grid infill. Additionally, with the increase in maximum load, the differences in maximum and minimum load between the print bed angles tested for each print orientation was reduced. The overall increase in strength with the gryoid specimens and decrease in difference of values could be due to the infill pattern. With gyroid infill, there is less variation with the pattern on the build plate, so the angle printed would matter less.

With the information collected from the experimental testing of the "dog bone" specimens, we can make recommendations to the users of the SLMP Makerspace. To start, for users to maximize the strengths of their parts, it is recommended to print in either the flat or horizontal print orientations so that the direction of load is not along the print orientation. Additionally, in order to make sure the print is more consistently strong, it is recommended to print using a gyroid infill in order to reduce potential variability in the print and reduce the reliance of print strength on the print orientation or print bed angle because the gyroid infill should provide more consistent behavior at different print bed angles within the layers.

5 MODULE

In addition to various research topics, an online training module was developed to help users better understand functional prototyping with 3D printing. This module will serve as a general reference for users who wanted to prototype with the printers in the SLMP Makerspace and will address issues commonly faced when prototyping with 3D printers. The information in this module is intended to help reduce the amount of prints failed due to inadequate knowledge in functional prototyping with 3D printing and help user speed-up their functional prototyping process.

5.1 Module Development

The training module is divided into two main parts: Tips for 3D printing individual prototype parts and how the part interacts with other parts. An outline of the module is listed below:

- Overview/Defining Functional Prototyping
- 3D Printing Slicing Settings to Consider
  - Infill
  - Layer height
  - Material
  - Orientation
  - Overhangs
  - Shells
  - Sizing/Scale
- Aspects to Consider when Designing for 3D Printing
  - Holes
  - Sharp corners vs. Fillets
  - Snap fit
  - Threaded inserts/Nuts
  - Tolerance
- Finishing the Part
- Additional Resources

The visual demonstrations printed for the SLMP Makerspace are also showcased on their respective slides. With the inclusion of these topics in the module, the SLMP Makerspace hopes to better educate users on aspects to consider when designing for functional prototyping with 3D printing.

6 CONCLUSION

The combination of online research, insight into other academic makerspaces, and experimentation into the effect of print orientation and print bed angle on specimen strength were all consolidated into a training module on functional prototyping with 3D printing for the members of the Spartan Light Metal Products Makerspace. To supplement the training module, visual demonstrations were 3D printing and placed around the SLMP Makerspace for member to interact with. Through the training module and visual demonstrations, we hope users will have more initial success with using 3D printing for functional prototyping and hope that instructors will be able to reference this training module in their courses.

In the future, development on this independent study would involve determining the effects of gyroid infill on the other print bed angles for each print orientation. This study is not exhausting and does not cover all possible print bed angles or print orientations, including those that are arranged in multiple axes. Further research could be into whether there is an ideal combination of print bed orientation and print bed angle that would maximize the maximum load or percent elongation of a specimen. Outside of print orientation, future work could be based on how 3D printed parts interact, including how 3D printed parts interact with other materials and how friction affects part interaction. This could also include how part attach to each other through the use of materials such as adhesives, mechanical attachments, and threaded heat set inserts.

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A Schematic Diagram

Figure 15 shows a labeled schematic diagram of the equipment.

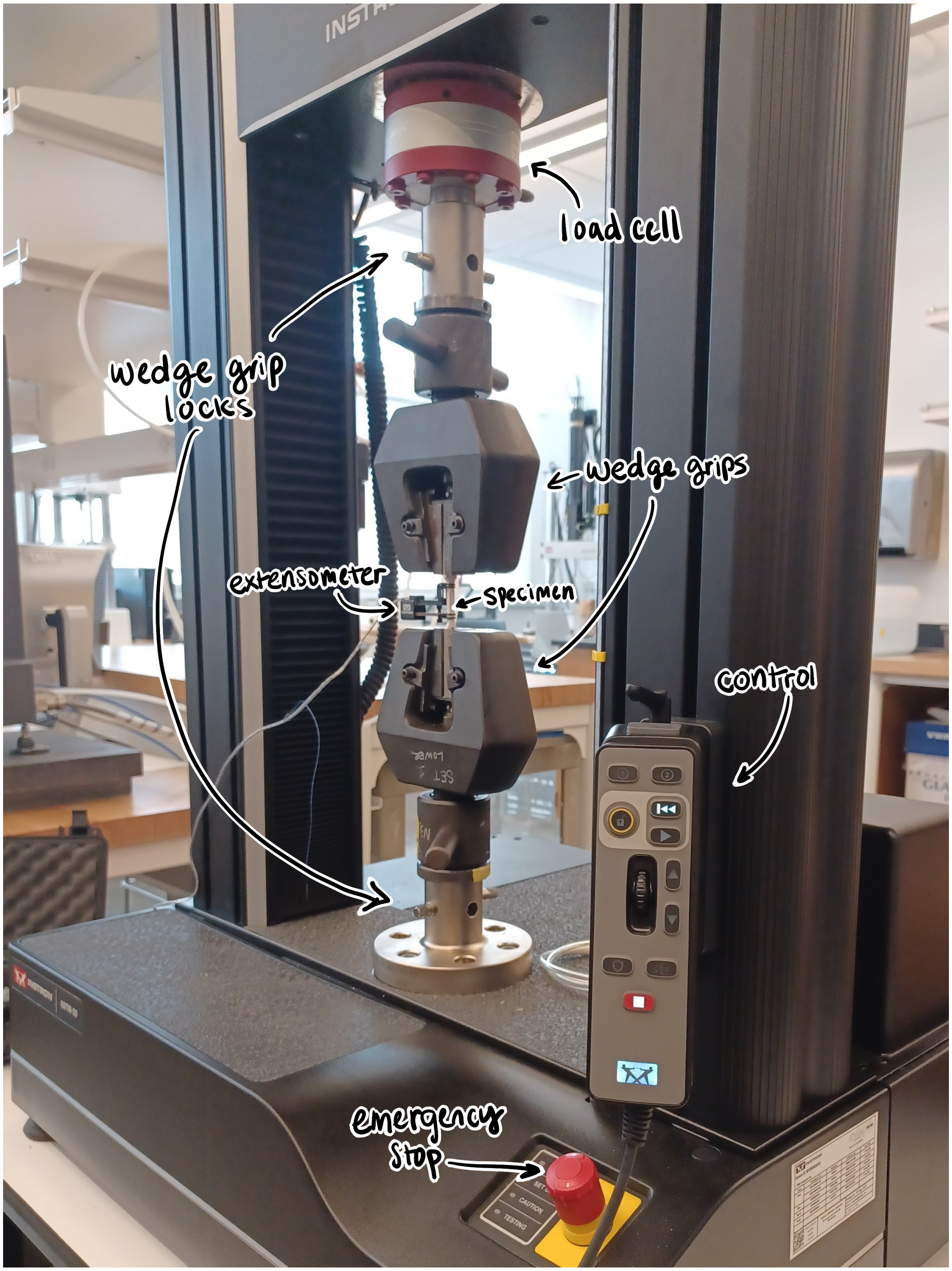

Figure 15: Schematic diagram of the experimental setup.

B Summary Data

Tables 6, 7, and 8 shows the summary data of various print orientations for grid specimens. Table 9 shows the summary data of the gyroid specimens.

Table 6: Summary data table of flat specimens.

PLA (0.2 mm) Prusa FLAT																
	Orientation (deg)															
Sample	-60		-45		-30		0		30		45		60		90	
	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]
a	1.75	569.15	1.84	599.09	2.01	594.42	1.79	516.74	1.58	539.26	1.7	558.18	1.78	566.74	1.88	557.3
b	1.66	560.88	1.84	576.89	1.88	573.47	1.78	535.79	1.69	557.13	1.69	549.39	1.72	549.15	1.88	560.98
c	1.79	588.8	1.88	607.19	1.67	568.57	1.8	530.69	1.78	566.34	1.71	558.59	1.68	531.41	1.89	561.7
d	1.73	569.74	1.81	597.85	2	575.14	1.8		1.8	572.14	1.7	547.83	1.74	546.76	0.03	574.92
e	1.7	559.14	1.69	561.17	1.89	575.01	1.81	527.99	1.73	576.88	1.71	542.19	1.79	546.09	1.84	562.05
Mean	1.73	563.54	1.81	588.44	1.89	577.32	1.8	529.12	1.72	562.88	1.7	551.59	1.74	548.03	1.8725	563.39
StdDev	0.05	5.45	0.07	18.91	0.13	9.93	0.01	7.57	0.09	14.86	0.01	7.06	0.04	12.58	0.01	6.72

Table 7: Summary data table of horizontal specimens.

PLA (0.2 mm) Prusa HORIZONTAL																
	Orientation (deg)															
Sample	-60		-45		-30		0		30		45		60		90	
	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]
a	1.72	554.2	1.66	604.85	1.8	524.77	1.8	544.61	1.65	548.85	1.59	599.52	1.66	544.65	1.73	572.1
b	1.73	547.82	1.75	555.08	1.65	532.44	1.73	558.12	1.66	556.28	1.68	561.17	1.66	541.85	1.74	568.5
c	1.7	543.47	1.74	628.06	1.8	540.85	1.73	553.04	1.68	561.77	1.64	549.34	1.63	530.72	1.73	555.66
d	1.74	560.74	1.74	537.08	1.78	525.79	1.74	568.09	1.69	561.21	1.75	630.93	1.72	538.91	1.74	562.2
e	1.85	553.04	1.69	552.92	1.69	538.75	1.67	562.54	1.68	556.29	1.66	571.45	1.72	545.1	1.76	571.41
Mean	1.75	551.85	1.72	575.6	1.74	532.52	1.73	557.28	1.67	556.88	1.67	582.48	1.68	540.25	1.74	565.97
StdDev	0.06	6.57	0.04	38.81	0.07	7.31	0.05	8.99	0.02	5.2	0.06	32.83	0.04	5.88	0.01	6.96

Table 8: Summary data table of vertical specimens.

PLA (0.2 mm) Prusa VERTICAL																
	Orientation (deg)															
Sample	-30		-45		-60		0		30		45		60		90	
	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]
a	1.13	363.63	1.44	341.7	1.31	352.28	1.44	392.39	0.98	337.58	1.26	358.05	1.05	307.78	1.32	355.59
b	1.15	320.37	1.47	356.68	1.06	299.42	1.4	398.89	1	336.75	1.44	345.67	1.03	350.8	1.17	342.19
c	1.02	310.54	1.48	352.24	1.25	331.45	1.41	345.06	0.97	294.15	1.41	347.35	1.19	327.4	1.19	310.12
d	1.17	306.36	1.34	401.95	1.24	328.35	1.38	389.31	0.91	290.59	1.28	330.94	1.26	384.67	1.79	390.47
e	1.24	327.22	1.38	338.3	1.09	350.37	1.38	329.21	1.02	298.57	1.36	349.98	1.17	323.73	1.59	431.5
Mean	1.14	325.63	1.42	358.18	1.19	332.37	1.4	370.97	0.98	311.53	1.35	346.4	1.14	338.88	1.41	365.97
StdDev	0.08	22.77	0.06	25.59	0.11	21.35	0.02	31.59	0.04	23.58	0.08	9.86	0.1	29.86	0.27	46.6

Table 9: Summary data table of gyroid specimens.

Gyroid Infill												
Sample	FLAT				HORIZONTAL				VERTICAL			
	0 L		-45 H		-30 L		45 H		30 L		0 H	
	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]	Maximum Load [N]	Tensile Strain (Displacement) at Maximum Load [%]
a	630.51	1.96	669.27	1.88	665.11	1.79	677.96	--	375.07	1.24	410.63	1.45
b	644.29	1.94	627.42	1.72	682.42	1.84	657	1.87	373.39	1.21	412.66	1.38
c	651.7	1.97	662.7	1.91	681.95	1.92	678.32	1.84	377.66	1.25	400.12	1.41
d	644.65	1.95	663.79	1.8	662.66	1.76	678.78	1.84	372.73	1.24	404.47	1.54
e	636.08	1.95	642.99	1.77	665.69	1.83	679.98	1.89	386.43	1.28	410.95	1.45
Mean	641.45	1.95	653.23	1.82	671.57	1.83	672.61	1.86	377.26	1.25	407.77	1.45
StdDev	8.24	0.01	17.53	0.08	9.76	0.06	9.29	0.02	5.4	0.03	5.28	0.06

Table 10 shows the detailed ANOVA results for grid specimens while Tables 11 and 12 show the summary ANOVA results for grid specimens. Tables 13, 14, and 15 show the summary ANOVA results for gyroid specimens.

Table 10: Detailed ANOVA results for grid specimens.

(a) Grid specimens' ANOVA results for maximum load.

Anova: Two-Factor With Replication (Maximum Load)				
SUMMARY	FLAT	HORIZONTAL	VERTICAL	Total
-60				
Count	5	5	5	15
Sum	2847.71	2759.27	1661.87	7268.85
Average	569.542	551.854	332.374	484.59
Variance	138.5738	43.10898	455.77933	12650.35
-45				
Count	5	5	5	15
Sum	2942.19	2877.99	1790.87	7611.05
Average	588.438	575.598	358.174	507.4033
Variance	357.6471	1506.71432	655.03778	12679.3
-30				
Count	5	5	5	15
Sum	2886.61	2662.6	1628.12	7177.33
Average	577.322	532.52	325.624	478.4887
Variance	98.47087	53.3909	518.30913	13068.27
0				
Count	5	5	5	15
Sum	2645.59	2786.4	1854.86	7286.85
Average	529.118	557.28	370.972	485.79
Variance	57.29067	80.93395	997.48102	7528.526
30				
Count	5	5	5	15
Sum	2811.75	2784.4	1557.64	7153.79
Average	562.35	556.88	311.528	476.9193
Variance	220.8204	26.9625	555.79012	14889.02
45				
Count	5	5	5	15
Sum	2756.18	2912.41	1731.99	7400.58
Average	551.236	582.482	346.398	493.372
Variance	49.78478	1077.95017	97.24647	12096.49
60				
Count	5	5	5	15
Sum	2740.15	2701.23	1694.38	7135.76
Average	548.03	540.246	338.876	475.7173
Variance	158.2299	34.51473	891.83333	10352.24
90				
Count	5	5	5	15
Sum	2816.95	2829.87	1829.87	7476.69
Average	563.39	565.974	365.974	498.446
Variance	45.1222	48.52008	2171.72153	10049.6
Total				
Count	40	40	40	
Sum	22447.13	22314.17	13749.6	
Average	561.1783	557.85425	343.74	
Variance	420.5472	547.9654097	1031.35176	

(b) Grid specimens' ANOVA results for percent elongation.

Anova: Two-Factor With Replication (Percent Elongation)				
SUMMARY	FLAT	HORIZONTAL	VERTICAL	Total
-60				
Count	5	5	5	15
Sum	8.63	8.74	5.95	23.32
Average	1.726	1.748	1.19	1.554667
Variance	0.00243	0.00347	0.01185	0.076398
-45				
Count	5	5	5	15
Sum	9.06	8.58	7.11	24.75
Average	1.812	1.716	1.422	1.65
Variance	0.00527	0.00153	0.00362	0.032471
-30				
Count	5	5	5	15
Sum	9.45	8.72	5.71	23.88
Average	1.89	1.744	1.142	1.592
Variance	0.01875	0.00483	0.00637	0.120846
0				
Count	5	5	5	15
Sum	8.98	8.67	7.01	24.66
Average	1.796	1.734	1.402	1.644
Variance	0.00013	0.00213	0.00062	0.032883
30				
Count	5	5	5	15
Sum	8.58	8.36	4.88	21.82
Average	1.716	1.672	0.976	1.454667
Variance	0.00763	0.00027	0.00173	0.125841
45				
Count	5	5	5	15
Sum	8.51	8.32	6.75	23.58
Average	1.702	1.664	1.35	1.572
Variance	7E-05	0.00343	0.0062	0.029431
60				
Count	5	5	5	15
Sum	8.71	8.39	5.7	22.8
Average	1.742	1.678	1.14	1.52
Variance	0.00202	0.00162	0.0095	0.081843
90				
Count	5	5	5	15
Sum	7.52	8.7	7.06	23.28
Average	1.504	1.74	1.412	1.552
Variance	0.67933	0.00015	0.07272	0.23536
Total				
Count	40	40	40	
Sum	69.44	68.48	50.17	
Average	1.736	1.712	1.25425	
Variance	0.08475795	0.002898462	0.03606609	

Table 11: Summary of ANOVA results for maximum force. Specimens with grid infill.

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Print Bed Angle	13406.25	7	1915.17866	4.444758	0.000257	2.106465
Print Orientation	1241805	2	620902.357	1440.994	2.52E-72	3.091191
Interaction	23223.52	14	1658.82305	3.849807	3.62E-05	1.796141
Within	41364.94	96	430.884752			
Total	1319799	119				

Table 12: Summary of ANOVA results for percent elongation. Specimens with grid infill.

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Print Bed Angle	0.4300725	7	0.061438929	1.743628	0.107906	2.106465
Print Orientation	5.89592167	2	2.947960833	83.66273	9.23E-22	3.091191
Interaction	1.012425	14	0.072316071	2.05232	0.021364	1.796141
Within	3.38268	96	0.03523625			
Total	10.7210992	119				

Table 13: Summary of ANOVA results for maximum load for the flat print orientation. Specimens with gyroid infill.

ANOVA					
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Print Bed Angle	6320.4346	1	6320.43458	31.99076674	3.58E-05
Infill Type	39216.139	1	39216.1392	198.4917883	1.95E-10
Interaction	2824.1138	1	2824.11378	14.29420146	0.00163787
Within	3161.1294	16	197.570588		
Total	51521.817	19			

Table 14: Summary of ANOVA results for maximum load for the horizontal print orientation. Specimens with gyroid infill.

ANOVA					
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Print Bed Angle	3485.328	1	3485.32802	10.5463285	0.005047377
Infill Type	66685.081	1	66685.081	201.7838108	1.72397E-10
Interaction	2775.368	1	2775.368	8.398045309	0.010485778
Within	5287.6457	16	330.477855		
Total	78233.423	19			

Table 15: Summary of ANOVA results for maximum load for the vertical print orientation. Specimens with gyroid infill.

ANOVA					
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Print Bed Angle	10159.68	1	10159.6796	25.20607411	0.000125554
Infill Type	13087.24	1	13087.2396	32.46932412	3.29669E-05
Interaction	1032.0534	1	1032.05345	2.560515344	0.129120175
Within	6449.0358	16	403.064738		
Total	30728.008	19			

C Makerspaces

The academic makerspaces researched are listed below:

- University of Wisconsin - Madison's UW Makerspace (Accessed September 20, 2023)
  - https://making.engr.wisc.edu/
- Harvard's REEF and SC Fabrication Lab (Accessed September 20, 2023)
  - https://seas.harvard.edu/reef-makerspace
  - https://projects.iq.harvard.edu/scmakerspace/home
- Princeton's PUL Makerspace, Keller Center Makerspace, and StudioLab (Accessed September 20, 2023)
  - https://library.princeton.edu/makerspace
  - https://kellercenter.princeton.edu/keller-center-makerspace
  - https://cst.princeton.edu/studiolab
- Duke's Lilly Library (Accessed September 19, 2023)
  - https://colab.duke.edu/locations-equipment/co-lab-studio-lilly/
- Yale's Center for Engineering Innovation and Design (Accessed September 19, 2023)
  - http://ceid.yale.edu/
- UC Berkeley's Supernode, Jacobs Institute for Design Innovation, and CITRIS Invention Lab (Accessed September 19, 2023)
  - https://supernode.berkeley.edu/
  - https://jacobsinstitute.berkeley.edu/
  - https://invent.citris-uc.org/
- Georgia Tech's Flowers Invention Studio, Yang Aero Maker Space, BME Design Shop, and MILL (Accessed September 11, 2023)
  - https://inventionstudio.gatech.edu/
  - https://ams.gatech.edu
  - https://bme.gatech.edu/bme/bme-design-shop
  - https://mill.mse.gatech.edu/
- Stanford's create:space, GSE Makery, and lab64 (Accessed September 11, 2023)
  - https://thehub.stanford.edu/services/use-makerspace
  - https://gse-makery.stanford.edu/
  - https://lab64.stanford.edu/

- Rice's oedk (Accessed September 11, 2023)
  - https://oedk.rice.edu/
- MIT's Makerworkshop (Accessed September 11, 2023)
  - https://makerworkshop.mit.edu/
- University of Washington - Seattle's MILL and GIX Prototyping Labs (Accessed September 10, 2023)
  - https://hfs.uw.edu/perks-recreation/the-mill
  - https://gix.uw.edu/
- Case Western's think[box] (Accessed September 5, 2023)
  - https://case.edu/thinkbox/
- NYU's Makerspace (Accessed September 5, 2023)
  - http://makerspace.engineering.nyu.edu/
- Carnegie Mellon's TechSpark (Accessed September 5, 2023)
  - https://engineering.cmu.edu/techspark/index.html

D Survey Questions

1. What best describes you at WashU?
   - First-year
   - Sophomore
   - Junior
   - Senior
   - Graduate
   - Faculty
   - Staff
2. How long have you been a member of the Makerspace?
   - <1 year
   - 1 year
   - 2 years
   - 3 years
   - 4 years
3. How often do you use the Makerspace?
   - Daily
   - Weekly
   - Monthly
   - Infrequently/As Needed
4. What do you use the Makerspace for? (Select all that apply)
   - Personal
   - Course
   - Research
   - Extracurricular
   - Other
5. What equipment do you use in the Makerspace? (Select all that apply)
   - 3D Printer (Prusa)
   - 3D Printer (Lulzbot)
   - 3D Printer (Form 3)
   - Laser Cutter
   - Vinyl Cutter

- Sewing Machine
- Drill Press
- Band Saw
- 3D Scanner
- Electronics

6. Briefly describe your experience with 3D printing. (This could include types of projects you've created, your history with 3D printing, etc.)
7. How many years of experience do you have with 3D printing?
   - <1 year
   - 1 year
   - 2 years
   - 3 years
   - 4 years
   - 5 years
   - >5 years
8. What software do you use to prepare files for 3D printing? (Select all that apply)
   - 3DPrinterOS
   - Cura
   - PreForm
   - PrusaSlicer
   - Other
9. Have you used 3D printers to create functional prototypes*? *Functional prototypes are defined as objects used to demonstrate the feasibility of a key aspect of a design.
   - Yes
   - No
10. Have you used 3D printers to create a final version of your design?
    - Yes
    - No
11. When prototyping with 3D printers, what difficulties have you encountered? (This could include difficulties with preparing your file to print, post-processing your print, etc.)
12. In your experience, what information would be useful to include in a training module on "Functional Prototyping with 3D Printers?"
13. What other types of 3D printing do you have experience with? (Examples could include metal printing, dual color, multi-material, flexible resin, etc.)

14. Rate your experiences with the following 3D printer materials: [Never heard of; Have heard of; Have used; Have used often]

    - Metal
    - Carbon fiber
    - Glass
    - Ceramics
    - SLS
    - Dual Color
    - Multi-Material
    - Flexible Resin
    - Polycarbonate
    - Nylon
    - PVA

15. With regards to 3D printing, what improvements/additions/etc. would you like to see implemented in the Makerspace?

16. What other improvements/additions to the Makerspace would you like to see?

17. Any other feedback for the Makerspace?

E JSON Output of 3DPrinterOS Slicing Profile (01. Prusa PLA 0.2 mm Speed)


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{
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    "machine_show_variants": true,
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       S{material_bed_temperature_layer_0} ; set bed temp\nM190 ...
       S{material_bed_temperature_layer_0} ; wait for bed temp\nM109 ...
       S{material_print_temperature_layer_0} ; wait for extruder temp\nG28 W ; ...
       home all without mesh bed level\nG80 ; mesh bed leveling\nG92 E0.0 ; ...
       reset extruder distance position\nG1 Y-3.0 F1000.0 ; go outside print ...
       area\nG1 X60.0 E9.0 F1000.0 ; intro line\nG1 X100.0 E21.5 F1000.0 ; ...
       intro line\nG92 E0.0 ; reset extruder distance position",
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"speed_prime_tower": 60,
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        "travel_avoid_distance": 0.625,
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        "cool_fan_speed_max": 100,
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      "conical_overhang_angle": 50,
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      "bridge_skin_material_flow_2": 100,
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      "bridge_fan_speed_2": 0,
      "bridge_skin_speed_3": 15,
      "bridge_skin_material_flow_3": 110,
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      "bridge_fan_speed_3": 0
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