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A STRUCTURED LOOK AT NEW DESIGN POSSIBILITIES FOR ADDITIVE MANUFACTURING MACHINES

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1. Introduction

There has always been a necessity for the creation of small-scale models for manufacturing processes prior to the full-scale production of a product. The production of these models exhausts a significant amount of time and resources, but is necessary to prove the capability and feasibility of new product ideas. In recent years, due to cost and demand, there has been a push for faster and cheaper production of prototypes. This is what led to the concept and technologies surrounding Rapid Prototyping (RP).

Rapid Prototyping is a relatively new concept, only having emerged within the last 30 years, with the aid of computers. Rapid Prototyping was originally defined as "A collection of technologies that are driven by CAD data to produce physical models and parts through an additive process." [Grimm 2004]. RP devices utilize Computer Aided Design (CAD) to render a three-dimensional (3D) computer model, which can then be formatted into two-dimensional (2D) slices and fed to an RP machine to create a model.

Since the introduction of 3D printers in 1987, there has been a lot of innovation. This paper will investigate the evolution of the designs of these machines in comparison to a theoretical "design space", to explore the potential for future development of more robust designs.

Unlike formative or subtractive processes, which remove or mold material, RP technology uses Additive Manufacturing (AM), which builds up material by creating 2D layers that are stacked upon and adhered to one another to create 3D objects. The first commercialized RP machine to utilize the AM method was the Stereolithography Apparatus (SLA-1), which was produced by 3D Systems in 1987 [Wohlers and Gornet 2014].

Modeling machines like the SLA-1, place their printing bed in photosensitive resins and use lasers, directed by mirrors, to adhere the resin in 2D layers and create models [Conley and Marcus 1997]. This method of RP is known as stereolithography (SL) and was the prevailing method for several years.

Shortly after the introduction of the SLA-1, many other companies, such as Sony/D-MEC and Electro Optical Systems, came out with similar SL machines. It wasn't until 1991 that the next big step in AM technologies came, when Stratasys developed the first fused deposition modeling (FDM) printer [Wohlers and Gornet 2014]. FDM was the first big shift away from stereolithography style printers, which was the predominant design. FDM printers work on similar principles, but with different media and printing methods. FDM works by taking a plastic, like Acrylonitrile Butadiene Styrene (ABS), and feeding it to a heated extrusion nozzle, which heats the plastic to just above its melting point, and extruding it in thin 2D layers that can be stacked to form models. Although this method is different from stereolithography, it still falls under the AM concept.

Since it’s inception, FDM style printers have come to be the most common style of printer. There are many reasons, such as the lower cost of raw materials, which may have led to this permeation of the market. But the main causal factor was the expiration of the patents covering the technology. The termination of the patents allowed individuals, such as Adrian Bowyer, to make the various design of printers free to access on the Internet [Hoskins 2013]. This led to the ability for consumers to construct their own printers, which in turn led to the rapid rise in the number of FDM machines. Although there are other types of AM machines, such as Selective Laser Sintering and Laminated Object Manufacturing, this paper will focus on the SL and FDM methods that are the most common.

These RP machines offer many benefits over traditional machining methods. Unlike milling and tooling, RP machines build up material in layers allowing for the machines to work with complex 3D shapes and design that would otherwise require multiple forms of machining [Mandellin-Castillo and Torres 2009]. This also results in very little waste produced and a reduction in the time required to make a model. Another benefit of this modeling technology is that it is relatively small and compact, when compared to other machining technology; allowing for the devices to be kept on a desk or table and not in a separate lab. With the convenience of speed and accessibility, designers are able to build and test their models more quickly and, if necessary, reiterate the process more swiftly. Prior to this, many designers would either have to go to a machining space and machine out their model themselves, or give their designs to a machining specialist who would construct it for them. This meant that there was additional time and money spent on the modeling process that RP technologies have reduced.

Though these devices have many beneficial aspects, like any new technology, they have many limitations and drawbacks affecting their performance. Such as how the term “rapid” implies that the process is fast; and it is faster than manual tooling processes, but the process, depending on the size of the object, can still take hours or even days. These RP tools are also limited by the initial start-up cost of buying the machine and materials, which is still relatively expensive for high quality equipment [Mandellin-Castillo and Torres 2009]. Also, the machines are restricted in the materials they can produce. Most technologies, including SL and FDM, are only capable of forming parts in various plastics. Likewise, both methods also require support structures, depending on the model's design, which are removed upon completion [Upcraft and Fletcher 2003]. Additionally, both tools also have problems with the parts warping with the changes in temperature during the production process. Although these limitations do affect the quality of the model process, they are not the major factors that restrict the use of RP technologies in manufacturing.

The main limitations that hinder the use of these machines in production processes are: the size of the model, the speed of the process, and the resolution capability of the machine. These three factors are the biggest obstacle that must be overcome in order for this technology to progress to a more finished state. Additionally, these limitations may be the result of many different mechanical factors that make up the design of the machines themselves. Certain design characteristics, such as axis orientation or frame design, may cause some inherent flaws in the machines. Likewise, these machines, in their current state, are susceptible to rough treatment, vibrations, movement, and various other environmental factors. In order to prevail over these problems, a more robust, industrial style printer needs to be designed. Ultimately, many hope that if these obstacles can be surmounted, the RP technology can be implemented in manufacturing processes to produce finished products, instead of being used for just prototyping.

This paper will take a structured look at the current, common, SL and FDM machines and define the different parameters that make up the different orientations and determine which of these parameters may impact the performance of the devices. Once the main characteristics are determined, permutations of each parameter will be generated and compared to the printer's performance to extrapolate any corollary characteristics. The ultimate goal of this project is to generate a chart, like a periodic table, of the possible parameters that make up these machines and to be able to generate new designs that assess the problems stated above [Allwood 2007].

2. Structured look for new designs

In its simplest form, RP machines can be broken down in several fundamental components: a solid building surface that is diametrically opposed to the head, a printing mechanism to process and place material, and the relative movement of the print mechanism in relation to the building surface. These components are the most important features in the functionality of an RP device. If there is a flaw, such as misalignment between the print-head and building surface, it will translate into a reduction in the machine's speed, printing quality, or even stop the process entirely and destroy the model. These three factors may be affected by many different parameters within the devices mechanisms, but the easiest way to reduce or eliminate any potential flaws, is to generate more robust machine designs that take these problems into consideration.

In order to obtain these robust designs, the underlying elements that make up the current designs, or their unused permutations, must be analyzed and compared to their performance, to determine which used or unused traits best address these problems. To do this, the attributes making up the machines, and all possible permutations of each, are identified and systematically viewed and compared.

2.1 General morphological methodology

General morphological analysis (GMA) is typically defined as “the rigorous examination and evaluation of all possible alternatives to each structural part of a problem.” [Foray and Grübler 1990]. This thought process, which also aims to remove preconceived biases from the evaluation of a problem, is the foundation of the morphological approach [Zwicky and Wilson 1967]. This approach seeks to address the multiple factors that constitute complex problems and break them down to their most fundamental traits. These typically non-quantifiable problems are prevalent in many different fields, but which this process is able to handle [Ritchey 2013]. Fritz Zwicky, the progenitor of this method, successfully applied his methodology to problems ranging from jet propulsion design to international policy analysis. This method can be summed up in the following steps:

- First: Precise identification of the problem to overcome.
- Second: The different characteristics surrounding the problem must be identified and studied.
- Third: Generation of a matrix or morphological box containing all the possible solutions to the problem.
- Fourth: Each solution is individually analyzed with respect to the problem.
- Fifth: The best solutions are identified and implemented [Ritchey 1998].

Zwicky first applied this method to his work at the California Institute of Technology, when working with jet propulsion engines. The problem that was identified was that a chemical powered propulsive engine was needed for jet planes. Zwicky then broke the problem down into six parameters, such as the state of the propellant and the type of ignition, and was able to generate 576 possible jet propulsion systems [Zwicky 1962]. 571 of these possible propulsion methods, were previously undiscovered. This meant that Zwicky was able to generate many new, potentially revolutionary, engine designs with his approach.

2.2 Morphological approach to rapid prototyping machines

Utilizing the morphological method, this project looks to review the current RP technologies and with the data gathered, generate new machine designs. The first step in the process is to identify the problem, which is that the current common SL and FDM machines do not produce at sufficient quality or reliable repeatability for full manufacturing capability. As stated previously, these machines can be broken down into three main parameters: the building surface, the material processing, and the relative motion. This paper will focus on the parameter of relative motion, by observing the orientation of the printing mechanism in relation to the printing platform. This was done first by breaking down the various forms of movement the printers can perform. It was broken down into 4 categories: (X, Y, Z), (R, Θ, Z), (Θ, Φ, Z), and (Θ, Φ, Ψ) motion. Then once these categories were determined, all their possible organizational permutations between the printhead (T in the tables) and build platform (B) were determined. This resulted in 8 possible orientation categories that the machines could be place in for each coordinate system. These design orientations make up the potential design space that is possible for these devices.

Once the potential design space was determined, a list of the most popular retail machines was selected from online sources and were organized into a table of the orientations. Table 1 shows the printers organized into their potential design space for X, Y, Z, oriented printers. This table shows that only part of the potential design space is utilized and some orientations are used much more frequently than others.

Table 2 illustrates the design space of the R, Θ, Z oriented machines with a few machines organized into their coordination. This second table reveals that only half the available space for the R, Θ, Z devices is employed. Tables 3 and 4 display similar information as the previous tables, but for the Θ, Φ, Z and Θ, Φ, Ψ orientation technologies. Both of these tables demonstrate how only 1 orientation is used out of 8 possible. These tables demonstrate how only a small portion of the potential design space is currently utilized for this technology.

Table 1-4. Table 1, left. Table 2, top right. Table 3, middle right. Table 4, bottom right

Printers:	X,Y,Z, Coordinate Machine Orientations							
	T:X,Y,Z / B:	T:X,Y / B:Z	T:X / B:Y,Z	T: / B:X,Y,Z	T:Y / B:X,Z	T:Y,Z / B:X	T:Z / B:X,Y	T:X,Z / B:Y
Zortrax M200		✓						
LulzBot Taz 5								✓
Ultimaker 2 Extended		✓						
MakerGear M2			✓					
Formlabs Form 1+							✓	
LulzBot Mini								✓
UP! Plus 2			✓					
FlashForge Creator Pro		✓						
AIO Robotics Zeus		✓						
FlashForge Creator		✓						
Dremel Idea Builder		✓						
RoBo 3D R1 Plus								✓
Printrbot Simple Metal								✓
UP! Mini			✓					
XYZ Printing Da Vinci 1.0		✓						
Printrbot Play 1505								✓
HICTOP Prusa i3								✓
B9 Creator							✓	
Rostock Max Delta Printer	✓							
Printrbot Simple 1405			✓					
Total:	1	7	4	0	0	0	2	6
Sources:	http://3dforged.com/best-3d-printers/#18							

Printers:	R,θ,Z Coordinate Machine Orientations							
	T:R,θ,Z / B:	T:R,θ / B:Z	T:R / B:θ,Z	T: / B:R,θ,Z	T:θ / B:R,Z	T:θ,Z / B:R	T:Z / B:R,θ	T:R,Z / B:θ
Polar 3D							✓	
*Theta Printer			✓					
**PiMaker								✓
Blacksmith Genesis								✓
*Polar-Scara				✓				
Total:	0	0	1	1	0	0	1	2
Sources:	http://3dprint.com/35656/polar-3d-printer-ces-2015/							
	https://hackaday.io/project/812-theta-printer							
	http://www.3ders.org/articles/20131227-rotary-3d-printers-under-development.html							
	*In pre-production and not yet readily available for purchase. **No longer comercially available							

Printers:	θ,φ,Z Coordinate Machine Orientations							
	T:θ,φ,Z / B:	T:θ,φ / B:Z	T:θ / B:φ,Z	T: / B:θ,φ,Z	T:φ / B:θ,Z	T:φ,Z / B:θ	T:Z / B:θ,φ	T:θ,Z / B:φ
*Makerarm	✓							
*FLX.ARM	✓							
Total:	2	0	0	0	0	0	0	0
Sources:	https://www.kickstarter.com/projects/1849283018/makerarm-the-first-robotic-arm-that-makes-anything/description							
	http://www.3ders.org/articles/20140917-flx-arm-low-cost-scara-robotic-arm-for-3d-printing.html							
	*In pre-production and not yet readily available for purchase.							

Printers:	θ,φ,Ψ Coordinate Machine Orientations							
	T:θ,φ,Ψ / B:	T:θ,φ / B:Ψ	T:θ / B:φ,Ψ	T: / B:θ,φ,Ψ	T:φ / B:θ,Ψ	T:φ,Ψ / B:θ	T:Ψ / B:θ,φ	T:θ,Ψ / B:φ
Mataerial				✓				
KUKA Arm				✓				
Total:	0	0	0	2	0	0	0	0
Sources:	http://www.mataerial.com							
	http://www.3ders.org/articles/20150203-students-develop-6-axis-kuka-abs-3d-printing-robot-inspired-by-spiderwebs.html							

Once the machines were organized into their respective tables, the performance characteristics were obtained from online sources and manufacturers information. The performance parameters, focusing on speed, build volume, and the resolution, were organized into tables. The max speed in cm3/hr was determined in order to compare the speed of FDM devices with SL. The SL machines use this speed measurement because they form a full layer at a time, whereas FDM printers print a bead of plastic to form a layer. This speed was determined by comparing the speed, nozzle diameter, and the largest layer thickness of the FDM printers. The majority of this data was obtained from the manufacturers websites and specification information.

Tables 5 and 6 show the performance data gathered on the various printer orientations. However, there is a great lack of specific dimensional data and much of the data required for a full analysis of these machines is not readily available from the manufacturer [Ralvas 2012]. Additionally, this data is not practical user data, but data gathered mainly from company documentation. In order to obtain more practical user data for these machines, an experiment was proposed.

Table 5 and 6. Table 5, left. Table 6, right

	Printer Orientations				
	T:X,Y / B:Z	**T:X / B:Y,Z**	**T:Z / B:X,Y**	**T:X,Z / B:Y**	**T:X,Y,Z / B:**
Nozzle Diameter (mm)	0.4	0.4	0.012	0.4	0.5
Min Speed (mm/s)	50	80	-	20	30
Max Speed (mm/s)	151	75	-	169	60
Max Speed (cm3/hr)	64	59	2.5	82	-
Build Volume (mm3)	6,391,098	5,170,631	2,086,244	8,654,483	23,100,000
Largest Layer Resolution (µ)	329	280	200	310	-
Smallest Layer Resolution (µ)	87	117	28	69	100
Precision X/Y/Z (µ)	9.74/7.76/2.73	10/10/2.5	-	11/11/04	-

	Printer Orientations					
	T:Z / B:R,θ	**T:R / B:θ,Z**	**T:R,Z / B:θ**	**T: / B:R,θ,Z**	**T:θ,φ,Z / B:**	**T: / B:θ,φ,Ψ**
Nozzle Diameter (mm)	0.4	-	0.4	-	0.4	0.3
Min Speed (mm/s)	40	-	-	-	8000 (ms/layer)	-
Max Speed (mm/s)	100	-	-	-	3000 (ms/layer)	50
Max Speed (cm3/hr)	58	-	-	-	-	-
Build Volume (mm3)	4,919,552	10,887,504	8,994,247	-	27,403,379	8,067,381,403
Largest Layer Resolution (µ)	400	-	200	-	-	-
Smallest Layer Resolution (µ)	50	-	50	-	100	300
Precision X/Y/Z (µ)	10/10/01	-	-	-	50/50/50	25/25/25

2.3 Test artifact experiment

This experiment was designed to gather practical user data that would better demonstrate the differences in the performance, based on orientation. The objective of this experiment was to produce models that would provide this data, specifically the dimensional performance of the machines in the various planes. Test artifacts have been utilized in previous research with AM processes, but most of the artifacts used in testing were built to compare the various AM methods, such as laser sintering printers and FDM printers, not to gather data between printers of the same method [Relvas et al. 2012]. For this purpose, a test artifact was specifically designed to test the dimensional accuracies of the various FDM machines. This design consisted of a small cube, measuring 25mm per side, with many surface characteristics, such as extruded and subtracted shapes, to better measure the performance capabilities of the printers on a range of feature sizes.

The artifact was designed so that each if its planes, X, Y, and Z, had an array of these characteristics to measure. The object was then arranged into a group of similar cubes, with identifying characteristics for placement, in order to cover the majority of the bed. This array was designed in such a way as to cover most of the printer bed for the various printers that would be tested. This was done to measure the accuracy across the entire build plane to see the variance between different portions of the printer bed. This data will be of use in further research, as the design of the bed support is investigated. An array of 3x3, or 9 cubes, was chosen so that a cube is printed in each corner, one in between each corner, and one in the center of the bed. Figure 1 shows a close up image of one of the individual cube as well as a snapshot of the array.

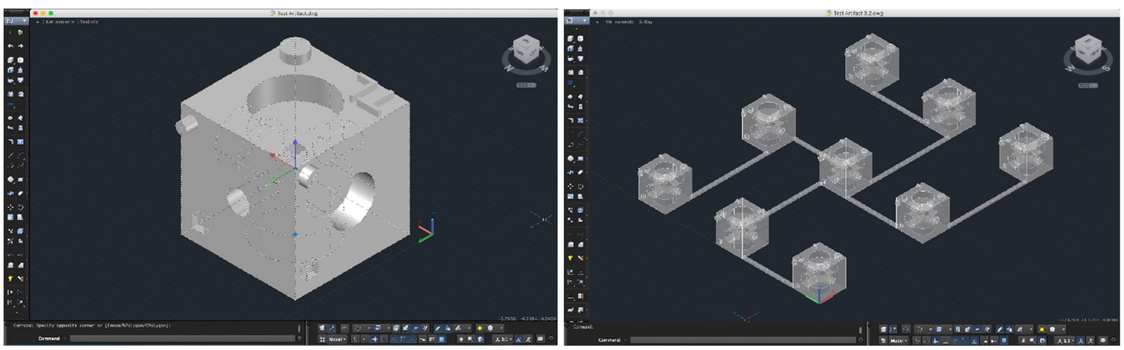

Figure 1. CAD models of test artifact

Once the individual cubes and the array were printed on the printer, the artifacts were measured comparatively to the CAD model design. This comparison showed the variance between the CAD model, which is the ideal measure, and what is produced from the printer, which is the practical outcome. Table 7, on the left, shows the measurement data gathered from the experiment conducted on an T:X, Y / B: Z oriented printer. Each design feature of the artifact was measured and the percent deviation from the ideal measure was calculated. Table 8, on the right, shows the measurement of the array's Z height across the build platform, measured with the print raft still attached and when it was removed. A raft was used in order to prevent major distortion due to warping. This data was gathered to see if the performance varied across the build platform.

Due to unavailability and technical difficulties, this experiment has only been conducted on an T:X, Y / B: Z printer at this time, but the experiment will be conducted on printers of other orientations in order to compare between them. Once conducted, the comparison between the printers should yield which design offers the best performance potential.

Tables 7 and 8. Test artifact measurement data

Plane 1		Plane 2		Plane 3	
Design Feature Size (mm)	Percent Deviation	Design Feature Size (mm)	Percent Deviation	Design Feature Size (mm)	Percent Deviation
5	-0.0076	15	-0.0008	10	-0.2678%
5	-0.0052	15	-0.0007	10	-0.3644%
2.5	0.0082	5	-0.0048	3.75	0.5373%
23.75	-0.0002	6.25	0.0001	24.375	0.0093%
23.75	0.0000	23.75	-0.0002	24.375	0.0029%
2.5	-0.0203	2.5	0.0004	2.5	-2.7022%
2.5	-0.0155	2.5	-0.0172	2.5	-2.3289%
20	-0.0001	20	-0.0003	20	0.0244%
2.5	0.0126	2.5	0.0098	2.5	0.4978%
25	-0.0002	25	0.0000	25	0.0100%

			With Raft	Without Raft
Front of Print Bed	TL Z Avg. Height	25.00	24.97	24.98
	TM Z Avg. Height	25.00	24.98	25.00
	TR Z Avg. Height	25.00	24.70	24.82
Middle of Print Bed	ML Z Avg. Height	25.00	25.09	24.98
	MM Z Avg. Height	25.00	25.11	25.01
	MR Z Avg. Height	25.00	25.03	24.95
Back of Print Bed	BL Z Avg. Height	25.00	25.07	24.94
	BM Z Avg. Height	25.00	25.10	24.98
	BR Z Avg. Height	25.00	25.01	25.00

3. Discussion

As previously stated, this paper seeks to review the current designs of RP technology, mainly common FDM machines, in order to determine which orientations of the design space offer the best performance.

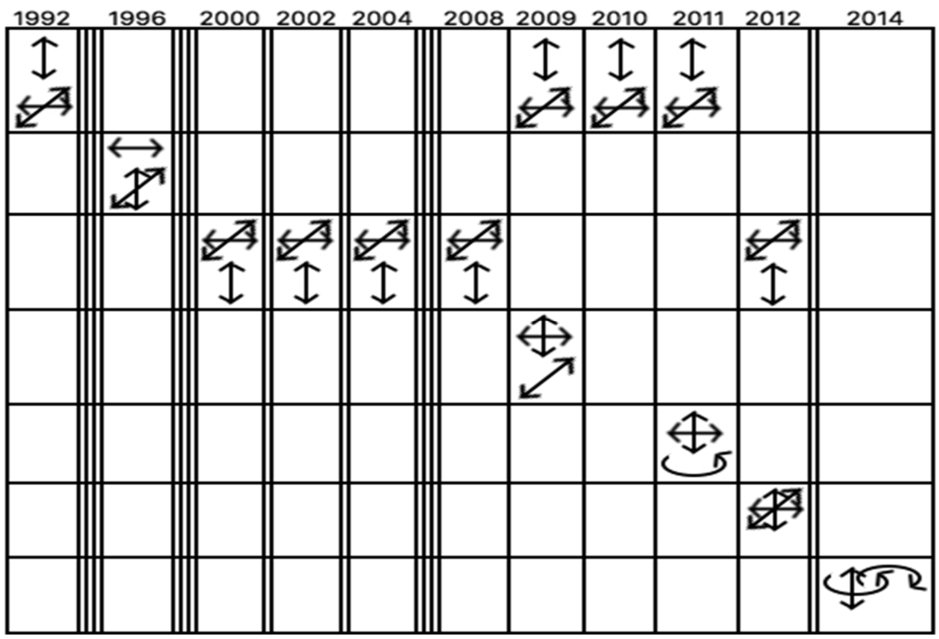

Figure 2. Design timeline

Through the course of this research, and as Tables 1-4 demonstrate, there is a significant amount of potential design space that is not used and this may be due in part to design fixation. In order to investigate this, a review of the history of FDM printer designs was conducted and a timeline of printer introductions was generated.

Design fixation is when designers tend to carry over characteristics from previous designs and those characteristics persist through designs that follow [Crilly 2015]. Figure 2 shows the timeline of designs that was generated from release dates of commercial FDM printers. The arrows in the figure represent the movement orientation, where the horizontal arrow represents X (or R for rotary printers), the vertical arrow Z, and the diagonal Y. The printers with rotary or angular moving parts are represented with curved arrows, such as the Polar 3D representation in 2011. The top half of each box represents the top of the printer and the bottom half, the bed. The vertical lines of the figure each represent a year, for example, there are 4 lines between 1992 and 1996. This is to show how long a design persisted before a significant change or different design was introduced.

The initial design of T: Z / B: X, Y, persisted as the sole design for 4 years and was still used by companies up through 2011. Only slight variations of this design were used in that time, such as the opposite orientation of T: X, Y / B: Z. It wasn't until almost 20 years after the first introduction of FDM printers, that a significantly different orientation design was introduced, such as the rotary printer in

2011. Now the reason that the X, Y, Z oriented printers, and the few utilized orientations within that category, might have persisted for so long may be because it is the best design or it may be due to design fixation. The fact that within the last few years, the designs have varied greatly into orientations of (R, Θ, Z), (Θ, Φ, Z), and (Θ, Φ, Ψ), would seem to indicate that the X, Y, Z orientations are not necessarily the best design and other potential orientations are being investigated. This information would imply that there was some design fixation for almost 20 years, but since 2011, the design variation has increased and new orientation methods are being introduced. Once more data is generated between the different printers and a thorough comparison is conducted, a more definite answer about design fixation can be given.

The initial data collected for analysis were taken from various sources on the Internet, specifically from manufacturer and retail websites when available, but much of this data had to be extrapolated from anecdotal sources, such as blogs and consumer reviews. There seems to be no standardized methodology for performance reporting and each manufacturer reports the data in ways that are most beneficial to their marketing. Some manufacturers, like Ultimaker, list their maximum speed for the printer head, but do not give at what resolution this speed was recorded or whether that speed is just the head movement speed or if it is the printing speed. The SL printers list their speeds in the form of volume per time, mainly because of its method of printing, but this data format is a more practical unit of measure for a potential consumer. The other reason much of the data was difficult to obtain, is because the machines of orientations other than X, Y, Z are either concept models that are in pre-production, new machines that have not been used by many, or were machines repurposed into printers, such as robotic arms. But all the available data were collected on these machines.

Once the initial data were gathered, it was analyzed to determine if there is any correlation between the orientations of the machines print mechanism and build platform, and how the machine performs. As shown in Tables 5 and 6, the printers oriented with their print head moving in the X and Z direction and their print bed moving in the Y, had the greatest speed and the printer with the head moving completely in the X, Y, Z had the greatest build volume in the X, Y, Z coordinate machines. The SL printers, although being the slowest printers, proved to have the best resolution, as you can see in Table 5. Further study will be needed to determine if this is due to the SL method of printing or if it is a result of the axis orientation.

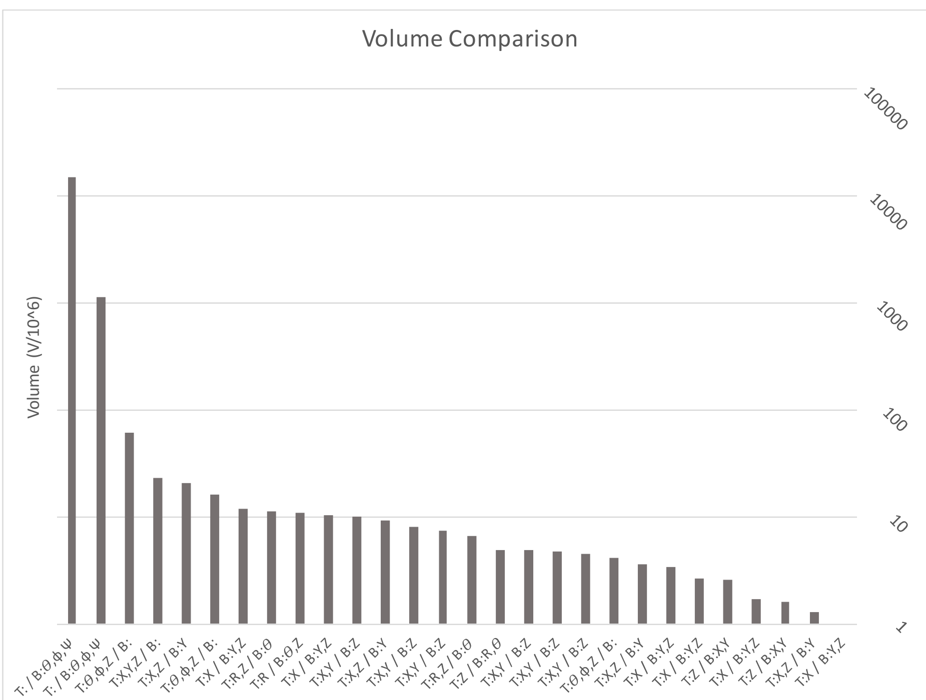

Figure 3. Printer volumes from all orientations

One characteristic that will not change with experimentation or investigation is the volume capabilities of the printers. This factor will stay constant and not vary through further testing. Tables 5 and 6 show the average volume data from the various printers. Most of this data was gathered from the manufacturers specifications and it shows a wide range of volume capabilities. Figure 3 shows that the Θ, Φ, Ψ printers offer the biggest build volume, but this may be due to the fact that the robotic arm printers themselves are very large. Out of the X, Y, Z, printers, the printer with the largest volume is the T:X, Y, Z / B:. The design of this printer allows for a greater height of printed parts and as a result, has a greater build volume compared to other printers of the same coordinate system. When you compare the printer volumes to the timeline figure above, you can see that the printers with the lowest volume capabilities are those that persisted from 1992 to 2011. Many of the new printer orientations after that have significantly increased the volume capabilities. This lends credence to the idea that the designs persisted so long because of design fixation, but that new designs are being investigated which have improved this feature.
Unfortunately, due to the lack of information, the X, Y, Z, printers can not yet be compared to the other orientations in speed or resolution. Once the experiment is conducted on other machines, a more thorough comparison can be made. But based on the initial information above; the machines with the greatest speed are FDM printers of the X, Y, Z orientation, the machines with the greatest resolution are SL machines of the X, Y, Z orientation, and the robotic machines of the Θ, Φ, Ψ orientation have the greatest build volume by far.
As stated previously, there are 4 orientation parameters broken down into 8 subsequent categories. These 32 possible designs make up the theoretical "design space" for these printers. Out of these potential designs, only a few are implemented. But are all these potential designs necessary? We will not know until the testing is done and all the possible orientations have been compared. We hope to determine which of the orientations, even those not currently used, could perform the best. Figure 4 shows an example of a 'periodic table' generated from the available design space. The portion labeled I is the X, Y, Z orientation, II being the R, Θ, Z, III being the Θ, Φ, Z, and the last portion IV being the Θ, Φ, Ψ orientation. Each of the 4 orientations was assigned a color with the darkest shade of each region representing the most common design, the second darkest region representing the next most common design, and lightest shade representing the designs that are rarely or never used. As Figure 4 emphasizes, there is a lot of design space that is not currently being exploited and which could potentially prove to be more robust designs. The fact that there is a lot of unused design space and that the majority of designs fall into very few categories, could again be a demonstration of possible design fixation.
In order to test the design space that is used and due to the significant lack of performance data, a test artifact was created to gather dimensional data for analysis. The measurement data from this experiment, shown in Tables 7 and 8, was further analyzed and put into graphical representation in Figure 5. The plot on the left shows the variation in measurements with respect to the size of the feature. As one would expect, as the feature size grows, the variance of the measurement decreases. This implies that larger objects should be more precise. Additionally, when a feature is 5mm or below, one can expect the printer accuracy to vary greatly. Each series of data shows the measurements from a different plane of the artifact. Using this data, the accuracy in the X, Y, and Z planes can be compared to see if there is significant difference in each dimension of the printer. Once data is collected from the other printers, this dimensional data can be compared between printers to better identify which design offers the best performance in all planes. More measurement data than what is displayed was collected from the test artifact and once other orientations are tested; a thorough analysis will be conducted to show the differences in design versus performance.

T:X,Y,Z / B:	I					
T:X,Y / B:Z					IV	T:θ / B:ϕ,Z
T:X / B:Y,Z		II		III	T:Ψ / B:θ,ϕ	T: / B:θ,ϕ,Z
T: / B:X,Y,Z	T:X,Z / B:Y	T:R / B:θ,Z	T:θ,Z / B:R	T:θ,ϕ / B:Ψ	T:θ,Ψ / B:ϕ	T:ϕ / B:θ,Z
T:Y / B:X,Z	T:R,θ,Z / B:	T: / B:R,θ,Z	T:Z / B:R,θ	T:θ / B:ϕ,Ψ	T:ϕ,Ψ / B:θ	T:ϕ,Z / B:θ
T:Y,Z / B:X		T:θ / B:R,Z	T:R,Z / B:θ	T: / B:θ,ϕ,Ψ	T:θ,ϕ,Z / B:	T:Z / B:θ,ϕ
T:Z / B:X,Y		T:R,θ / B:Z	T:θ,ϕ,Ψ / B:	T:ϕ / B:θ,Ψ	T:θ,ϕ / B:Z	T:θ,Z / B:ϕ

Figure 4. Example of a periodic table of designs

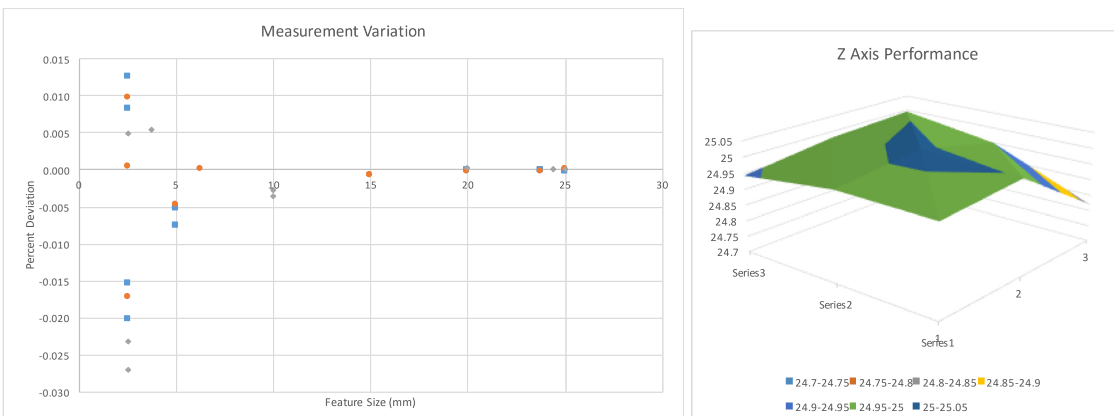

Figure 5. Printer measurement variations and performance

The plot on the right of Figure 5 shows the Z axis performance across the build plate. Series 1 on the figure represents the front of the build plate, series 2 represents the center, and series 3 represents the back. Numbers 1 through 3 represent left to right respectively. This data shows that the greatest accuracy occurs at the center of the build platform and that the greatest variance occurs at the corners. This data will be useful as the next step in this research project will be to breakdown the the building platform in a morphological way and to investigate its traits and performance. Then once there is sufficient data, a full periodic table of robust machine designs, with all the subsequent traits, can be generated.

This project broke down the current, common, SL and FDM machines into their different orientations and permutations and then reviewed the data taken from manufacturers and retailers. It was determined that the data obtained from these sources was insufficient and an experiment to gather practical user data was designed and performed. The next step in this research project will be to conduct this experiment on other printer orientations and perform an in depth comparison of the dimensional performance. Then following that, the printer bed design will be investigated in a similarly structured way. The ultimate goal of this project is to determine which possible designs mitigate the problems discussed previously and offer the best printer performance; and with this information a “periodic table” of designs that contains all the possible printer designs, including the robust solutions, will be generated.

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