Identifying the Main Effects that Cause Spatial Variation in a Stereolithographic 3D-Printer with a Test Target and Graphical Analysis

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Identifying the Main Effects that Cause Spatial Variation in a Stereolithographic 3D-Printer with a Test Target and Graphical Analysis

By Joseph V. Kain

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Print Media in the School of Media Sciences in the College of Imaging Arts and Sciences of the Rochester Institute of Technology

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Abstract

This thesis investigates a stereolithography printers’ ability to resolve converging features within its build volume. This experiment employs the use of a Formlab Form 2 stereolithography device to create Geometric Element Test Target (GETT) artifacts designed in Solidworks. The sample will consist of a global arrangement of test artifacts in predetermined positions from a fractional factorial design of experiments. Each local sample will be a slanted ray GETT with designed wedge heights of 1 and 2mm. The finished array of samples are photographed and cataloged for graphical analysis. The ray step heights will be measured using a caliper and graphical analysis to observe any deviation from the digital file with respect to its volumetric arrangement. Similarly, the minimal producible width of the device will be calculated by measuring the wedge angle of the rays and the diameter of the region that cannot be produced by the printer, this will be done by using graphical analysis. The addressability of the device will be measured by counting the number of steps and dividing the measured heights by that number.
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I would like to share my final thanks to my family all of my aunts, uncles, cousins, and grandparents, especially John and John for keeping me sane and reminding me that there’s always time to laugh and enjoy life with those around you. Lastly, I would like to thank my mom, dad, and sister for whom I dedicate this thesis to. Your unconditional love and support has been the bedrock of my educational career and my life as a whole, know that I always take with me the lessons you’ve taught me and the love you’ve given me. Love always, your son and brother, Joe.
Chapter 1: Introduction

Three-dimensional (3D) printing is a method of manufacturing that is additive instead of subtractive, this is also known as additive manufacturing (AM). (ASTM F42, 2016). Additive manufacturing is “the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative methodologies.” (ASTM F42, 2016).

Over the past ten years the size of the AM industry has grown tremendously. According to Wholers Report 2014 the value of the market has grown from $750 million to $3.07 billion in the decade from 1994-2013 (Wholers, 2014). The size of the AM market, encompassing all products and services, grew 34.9% to $3.07 billion in 2013 (Wholers, 2014). With a value of $3.07 billion in 2013 the industry is expected to reach a value of $12.5 billion in 2018, and $21 billion in 2020.

Additive manufacturing is an important technology because of its reach in many applications, visual aids, presentation models, prototypes for fit and assembly, patterns for prototype tooling, patterns for metal castings, tooling components, functional parts, and education/research (Bogue, 2013; Wholers, 2014). The part production segment of the AM industry contributes 34.7% of total product and services revenues to a total of 1.065 billion in 2013 up 56.5% from 2012. (Wholers, 2014). This technology has the ability to create customizable parts with complex features and geometries that are unable to be produced by traditional manufacturing method. Areas of business that are utilizing this feature...
of 3D printing include automotive, medical, aerospace, industrial/business machines, academia, government/military, architectural, and consumer goods to produce individualized parts with minimal start-up. (Brogue, 2013; Wholers, 2014).

Additive manufacturing technology has a role in many different industries but still struggles to penetrate into end-use products. Limitations that hinder this include but are not limited to accuracy, imperfections, limited choices of materials, and low throughput (Pan et al., 2017). In 2017 Bikas states that resolution limitations and dimensional accuracy have been the topic of many studies attempting to model the product of an SLA device (Bikas, 2016). However, a majority of these are theoretical models and have not been verified with experimentation (Bikas, 2016).

One of the biggest barriers to the implementation of AM technologies is the lack of standardization in devices, processes, and final products (Savastano et al., 2016). The fundamental principle of additive manufacturing is the creation of a 3D object by the continuous addition of discrete quantities of material. Within this general definition there are multiple different processes (ASTM F42, 2016). The AM process used in this study is vat photopolymerization or stereolithography which is a process in which a liquid photopolymer in a vat is selectively cured by light-activated polymerization layer by layer. (ASTM F42, 2016). Current SLA devices typically build with an x-y resolution of 50-200
microns (Pan et al., 2017). This study will analyze the problems with resolution and accuracy of final products from an SLA device.

The AM industry is currently faced with an issue of quality. This has been the subject of research for many years (Wholers, 2013). The quality of AM printed parts has increased through the years and thus the need for a more effective method of device evaluation is needed. In order to better understand the precision of AM devices test artifacts have been used to measure device performance. These artifacts usually consist of multiple geometric shapes in both positive and negative space on the artifact. The features are then measured, most commonly, by a coordinate measuring machine (CMM). A CMM is a device that uses a laser to scan the surface of the artifact and relays the measurement data to the user. This data can then be compared to the original digital file to see where the printer struggles to produce the artifact correctly, however this process is very inefficient and cumbersome making its viability as a method for process control and not just experimental quality assessment unfeasible.

This study will utilize the geometric element test target (GETT) methodology to test process capabilities (Chang et al., 2015). GETT creates a test artifact that is designed to make the printer fail, or in other words create a feature that the device is unable to reproduce such as a singularity. The artifact consists of simple geometric shapes or lines in a repeated pattern, such as concentric circles or ray convergence (Chang et al., 2015). The failed area of the GETT artifact is measured and the device’s true resolution is able to be
determined based on the printer’s settings and the parameters of the artifact. This methodology is designed to be a simple and effective way of visually determining a printers’ capabilities without the need of a CMM or other measurement device (Chang et al., 2015).

Currently the GETT methodology has only been used on FDM printers, this study will utilize a SLA device. Using six varying parameters, x, y, and z dimensions, GETT orientation, slice height, and material change, the GETT methodology will be applied to the SLA process and measure the capabilities of a Formlab Form 2 SLA device using a fractional factorial design of experiment (DOE). This study aims to employ a method for quickly evaluating the capabilities of an SLA device using a GETT artifact and methodology.

Statement of the Problem

As 3D printing becomes a viable option in the $12 trillion manufacturing market (Nigro, 2018) the need for a fast and easy method to determine the cause of dimensional variations becomes clear. Therefore this research seeks to identify the main effects that influence the spatial variation in a 3D printing device.
Chapter 2: Theoretical Background

Within a process or system there are many factors, some can be changed while others are uncontrollable. Conducting an experiment is a way of determining the effect of these different types of factors on the process or system.

This chapter will discuss the features of an experiment and how an experimental design can be used. Evidence supporting the use of a factorial experimental design is shown and why it is important for certain types of experiments. This chapter concludes with an examination of GETT and graphical analysis to illustrate the benefits of using this methodology.

Variation of a Process

Montgomery defines an experiment as “…a test or series of runs in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response.” (2013) In each experiment there are input variables, controllable factors, and uncontrollable factors (x’s) as well as the output (response variables, y’s) as demonstrated in Figure 1.
Figure 1 shows the general model of a process or system. This system can be paralleled to the system of baking cookies. In this example the process, middle box, will be the act of baking cookies. The controllable factors will be things that can change but are held constant, in this example they are oven temperature, and cook time. The uncontrollable factors are parts of the process that are unavoidable but can be accounted for, in this example they are altitude, humidity, and other environmental factors. The inputs are parts of the process that are altered to determine their effect on output, in this example they are the amount of flour, sugar, and eggs in the recipe. The output is the result that is measured based on the input factors, in this example the outputs are the taste,
color, and texture of the finished cookie. There can be many factors in an experiment and each factor can have different and multiple levels, or in other words values, in the experiment.

According to Montgomery, the objectives of an experiment include:

- Determining which variables are most influential on the response y
- Determining where to set the influential x’s so that y is almost always near the desired nominal value
- Determining where to set the influential x’s so that variability in y is small
- Determining where to set the influential x’s so that the effects of the uncontrollable variables are minimized (Montgomery, 2013)

The best way to approach these objectives is with a strategy of experimentation that best suits the experiment at hand. Three different types of experiments that Montgomery (2013) alludes to are the best-guess approach, one-factor-at-a-time (OFAT) approach, and a factorial experiment. The best-guess approach is when experimenters do not know which factors will influence the process so they guess which ones they think will have an effect. This can be a lengthy method of experimentation if the guesses are not correct. The OFAT approach to experimentation is when one factor in an experiment is varied and the others are kept constant. This is a lengthy process but will show the effects of the factors on the process but not interactions between the factors themselves. Due to these reasons neither of these types of experiments are the best choice for an experiment dealing with multiple factors. According to Montgomery the
ideal type of experiment to use for a multi-factor experiment is a factorial design, and thus will be used for this experiment. (Montgomery, 2013).

**Experimental Design**

The factorial design of experiments utilizes a factor and level approach to an experiment. Each factor has specific levels that are used throughout the experiment to determine causal relationships with the output. This concept is illustrated in a fish bone diagram in Figure 2. Each of the factor arrows can have a certain amount of levels, or values, associated with it for each particular experiment.

![Fish bone diagram of factors and in a factorial design](image)

In order to distinguish the factors that most affect the spatial variation of the print the use of a factorial design of experiment (DOE) will be employed. The of a factorial design according to Montgomery is the most efficient when studying
the effects of two or more factors. (Montgomery, 2013). This experiment will utilize this approach to understand the change in response of the y’s by changing the level of the x’s. In this research the DOE will measure the effect that the six factors (x’s) have on the resolution and addressability (y’s).

Factorial designs have many advantages over OFAT designs including being more efficient, and allowing the effects of a factor to be estimated against other factors across a range of experimental conditions. (Montgomery, 2013). Fractional factorial designs use a fraction of the total number of treatment combinations in an experiment. (Kirk, 1982). The major use of fractional factorial design is in screening experiments where there are many factors and the goal is to understand which factors are main effects on the process. (Montgomery, 2013). The reason a fractional factorial is used instead of a full factorial is because as the amount of factors increase the number of runs required to test all possible interactions increases as well, as a result the number of higher order interactions grow and obscure the results of the lower order, main effect, interactions. (Hamada et al., 2009). According to Jaynes (2013) using a full factorial for a six factor experiment is wasteful and the use of a fractional factorial is a more practical and economic way to estimate the effect of low order interactions.

The implementation of a fractional factorial design has different levels of experimental resolution at which the experiment can be carried out. The first type is resolution III which means that the main effects are intertwined with two-factor
interactions. (Montgomery, 2013). This means that any effect on the output could be the result of any two factors in the experiment. Resolution IV means that the main effects are not aliased with any other main effect or any other factor to factor interaction, instead factor to factor interactions are aliased with each other. (Costa et al., 2010). The use of a resolution IV design breaks as many higher order interactions as possible so that the experimenter is left with low order, one-factor interactions. This resolution works well when dealing with many factors to eliminate any unwanted results or interactions. Illustrated in Table 1 is the difference between the full and fractional factorial. The number of runs is shown in the last row of the table, from this the difference between a full and fractional factorial can be observed and it can be determined that it is more efficient and economical to do a fractional factorial for this experiment.

Table 1.

<table>
<thead>
<tr>
<th>Full vs. Fractional Factorial</th>
<th>Full</th>
<th>Fractional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>$2^k$</td>
<td>$2^{k-p}$</td>
</tr>
<tr>
<td>k: Number of Factors</td>
<td>6</td>
<td>6(IV)</td>
</tr>
<tr>
<td>Number of Runs</td>
<td>64</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 1 shows the difference between full and fractional factorial experimental designs. The first row in the table shows how the design calculates the number of runs for each type of experiment, the letter ‘k’ represents the
number of factors in the experiment and the letter “p” is determined by the resolution of the experiment, in this case it is IV. The number of runs is shown in the last row of the table.

Quality Assessment

The following section will discuss the use of quality assessment in the manufacturing and print industries. The use of test targets and coupons in these industries lead into the GETT methodology and how they relate to each other.

Manufacturing. The use of test coupons is ubiquitous in the manufacturing industry. They are specifically designed to test the properties of a part being produced to ensure its fidelity to the specifications. Test coupons are small representations of a larger part that undergo testing to understand the capabilities of the design and material. Many coupons can be produced at a time to create a statistically significant sample so the manufacturer can be certain of a part’s properties.

Test coupons are tested and retested until it is determined that the parts are of the highest quality, this is an integral part of the manufacturing process for new materials and methods (Orme et al., 2017). Properties that test coupons are tested for, according to these researchers who are speaking of powder-based parts, include but are not limited to pressure, porosity, hardness, and tensile testing (Brune et al., 2017; Orme et al., 2016; Orme et al., 2017). Test coupons
are manufactured with the component to ensure the part is devoid of defect that could lead to part failure (Orme et al., 2016).

**Printing.** Test coupons in manufacturing can be related to the use of test targets and process control in the traditional printing industry. These test targets assess the printers’ ability to reproduce fine lines, shapes, and images across different technologies and specifications (Sigg, 2006). The targets determine the resolution capabilities of the device based on the current settings of the printer.

Print resolution and addressability are both features of two-dimensional printing that are measured using test targets. According to Sigg (2006) resolution is a function of contrast and a curve is required to describe the capability of the device while the addressability is referred to in dots/spots per inch. An example of a test target used in two-dimensional printing is a spatial resolution test target. Spatial resolution, according to Madhavji, is “the minimum distance between distinguishable objects in an image.” (Madhavji, 2010) The test target, shown in Figure 3, consists of alternating black and white lines converging to a singularity the printers’ spatial resolution is determined by which region distortions are able to be seen.
Figure 3: Spatial resolution test target used for identifying the spatial resolution of a printing device.

In order to interpret this test target an observer identifies the regions where the individual lines begin to distort. This group of lines corresponds to a certain width. That width is the devices’ spatial resolution. The results of this test are achieved through the use of visual analysis which is the idea behind the GETT methodology and its use in 3D printing.

**GETT and Graphical Analysis**

GETT targets test the dimensional and geometric viability of three dimensional printers. GETT targets are unique and complementary to those currently available (Chang et al., 2015). These targets are designed to induce failures that display the devices’ limitations which can be visually inspected or evaluated through the method of graphical analysis. This methodology is derived from the use of test targets in two-dimensional printing and test coupons in the manufacturing industry.
**GETT.** Using the idea of test targets and device specific capabilities geometric element test target (GETT) can be used for additive manufacturing devices. This draws from the use of test coupons in the manufacturing industry and test targets in the printing industry. Similar to both uses, GETT allows the operator to understand the capabilities, limitations, and performance of the device based on the settings being used to create a part.

**Graphical Analysis.** Visual analysis is a way of representing data and can take a multitude of forms according to Kehrer et al. (2013). Methods of visual analysis span across multiple fields for many different uses.

Andrienko et al. (2011) used a visual analysis method to map areas of high traffic volume surrounding the city of Milan. They did this by using arrows of different sizes to show both the magnitude and direction of the traffic, this was overlayed onto a map of the city for a clear representation of the data (Andrienko et al., 2011).

In a study conducted by Ruschin-Ramini et al. visual analysis was used in a manufacturing setting to improve quality. (2012). Their approach involved visual analysis to find defects in operational sequences along the production route of a part. The use of visual analysis in this setting requires no understanding of mathematical or statistical algorithms which makes the process of identifying problems in the data more intuitive and easy to understand (Ruschin-Rimini et al., 2012).
The use of graphical analysis as a means of visual inspection for 3D printed GETT artifacts offers a faster, more practical method of 3D printing device assessment. This process works by overlaying graphical grids onto the physical part and estimating the differences as shown in Figure 4 (Li et al., 2016). The process of graphical analysis is an important part of the GETT methodology because it allows the user to quickly and accurately estimate critical values for device assessment such as wedge angle, forbidden circle diameter, and wedge width (Li et al., 2016).


Figure 4 demonstrates the use of graphical analysis to estimate the failed regions of the GETT target. The first two frames of Figure 4, respectively, show the original 3D printed target and how the target failed to reproduce in the blue
circle. The third frame in Figure 4 shows the first graphical analysis grid, a series of concentric circles with a constant distance from each other can accurately estimate the failed region at the center of the ray GETT. The ray GETT is a test artifact that contains a series of rays, or wedges, that converge to a singularity. This type of artifact is important because the device will be unable to reproduce the singularity and the defects can be measured to assess process capabilities. The fourth frame of Figure 4 shows the use of a graphical analysis grid to measure the angular width of the rays, each of the lines in the grid are equidistant apart. The lines are then counted and give an accurate estimation of the angular width of the rays in the GETT.

**Analysis of the Variance (ANOVA)**

Analysis of the variance (also known as ANOVA) is a common method of statistical analysis for an experiment. In order to conduct an ANOVA on data there are three requirements that must be met (Andersen et al., 2015):

1. For each population the response variable is normally distributed
2. The variance of the response variable is the same for all populations
3. The observations must be independent

The analysis of the variance includes “…two independent estimates of the common population variance… one estimate is based on the variability among
the sample means themselves, and the other estimate is based on the variability of the data within each sample.” (Andersen et al., 2015). By using these two variances an inference on the means of the populations can be made to prove or disprove the null hypothesis.

**Conclusion**

This concludes the theoretical background of this thesis. In this chapter the implementation of a fractional factorial design is presented and defended by explaining its benefits when used in an experiment with many factors. The use of GETT is also discussed and shown to be a useful tool for quality assurance among AM devices. The chapter terminates with a discussion of the benefits of using graphical analysis for means of data analysis and ANOVA.
Chapter 3: Literature Review

Introduction

In this chapter a thorough review of the literature surrounding the topic of this thesis is conducted. This chapter will begin with the factors affecting stereolithography print quality and why they are important, followed by additive manufacturing test artifact usage and the implementation of the GETT methodology, and finish with a review of factorial experimental designs and graphical analysis.

Stereolithography (SLA)

Stereolithography is a 3D printing technology that utilizes UV curable photopolymers to generate 3D objects. This means that the print bed sits within the UV curable resin and is raised or lowered as a UV laser cures the resin to create a solid figure. The entire STL process is as follows according to Gibson et al.:

1. CAD file must be converted into a .stl file and then into “slice” file to be read by the printers’ software.
2. Resin must be loaded into the vat and the build plate is lowered into the resin so that the top of the plate is just covered with the resin.
3. The UV laser traces out each layer which is defined by the slice file.

4. After each slice the build plate drops and the surface of the vat is recoated to prepare for the next slice.

5. Once the object is printed it must be cleaned, post-cured, and finished.

The materials used in the SLA process are photopolymers. This process is limited to photopolymers and will not support different resins due to the nature of the SLA process. There are two types of photopolymers which are acrylate based and epoxy based (Zhang, 2014). Methods of curing photopolymers include “…gamma rays, X-rays, electron beams, UV, and in some cases visible light, although UV and electron beams are the most useful.” (Gibson et al.). There are different photopolymerization processes when it comes to SLA printing which are dependent on the type of STL printer being used.

SLA has many different factors that go into the printing process such as input factors: layer thickness, orientation of the part, vat location of the part, and material change, uncontrollable factors over-cure, under-cure and control factors exposure intensity, exposure time, and ambient temperature. (Gowda et al., 2014; Schaub et al., 1997; Ghadami et al., 2014; Zhou et al., 2000; Taft et al., 2011):

- Layer thickness: thickness of each slice of the part being built
Factors Affecting Stereolithography Print Quality

The quality of an SLA printed part, in regard to its dimensional accuracy, is determined by many factors that can be controlled through the design of the part and the settings on the device itself. Studies over recent years have analyzed the SLA process and have concluded certain factors that contribute to print quality. Below, certain factors will be examined more carefully.
Layer/Slice Thickness. Layer thickness, which means the thickness of each slice of the part building on the previous layer, has been found to be a factor in the quality of SLA printed parts according to the studies in this section. This section of the chapter will review three different studies in which layer thickness was found to be a contributing factor to the quality of SLA printed parts.

Zhou et al. conducted a study of twenty-seven runs in which layer thickness, among other factors, were tested for their impact on the quality of printed parts in terms of accuracy on an SLA device (2000). Using a Taguchi design, they found that layer thickness had a significant effect on all features of the test part as well as the surface finish of the printed part (2000). Through this experiment Zhou et al. were able to conclude that using a lower layer thickness yields a more dimensionally accurate printed SLA part.

In a study conducted by Ghadami et al. the layer thickness of SLA printed parts was tested to observe its impact on dimensional accuracy (2014). They studied four parameters, layer thickness, hatch spacing, hatch over cure and hatch fill cure depth, in an artificial neural network which is an experimental design to predict the dimensional accuracy of SLA printed parts. The accuracy of this design was tested over three sample artifacts and could account for the SLA process with an average error of 6%. Using the results from the CMM measurements of the test artifacts this experiment shows that layer thickness is the most important parameter when concerned with dimensional accuracy. (Ghadami et al., 2014).
In a recent study conducted by Chockalingam et al., slice thickness was a parameter studied to observe its impact on different types of features on a test artifact. The test artifact is studied based on its different features, parallel, perpendicular, angular, and concave radius features as well as surface roughness (2014). Chockalingam et al. found that layer thickness had the largest effect on parallel features and surface roughness which were measured using a coordinate measuring machine (2014). This was done through the use of a Taguchi design of experiment.

These studies show the impact of layer thickness on part quality of SLA devices and how important it is to study this factor in the SLA process.

**Part Location and Orientation.** In addition to layer thickness, the location of the part in the build volume was also tested for its effect on the quality of parts produced. Studies conducted by Zhou et al., and Taft et al. investigated the differences in part accuracy with respect to its position in the build volume (2000; 2011). The Zhou et al. study examined many different process parameters for the SLA process including layer thickness, hatch spacing, overcure, blade gap, and position on the build plane. The results of this study showed that a part with a low layer thickness printed close to the center of the build plate yielded the best results. (Zhou et al., 2000). The Zhou et al. study, however, only considered varying the part location in the x-y plane in three different spots (inner, middle, and outer) (2000).
In a recent study conducted by Taft et al. position in the build volume of an SLA device was investigated to determine its impact on dimensional accuracy (2011). The study investigated the differences of an SLA printed model skull at different points on the part using a CMM, seven different models were tested in this study (Taft et al., 2011). Taft et al. found deviations in the x, y, and z directions throughout the print when compared to the control part. The deviations in the x-y direction were much less than the z-direction which was largely impacted by slice thickness (Taft et al., 2011).

Orientation of the printed part on the build platform in an SLA device also plays a role in its quality. Research conducted by Gowda et al., Puebla, and Zhang et al. shows the effect of part orientation on print quality (2014; 2009; 2016). While not directly related to the dimensional accuracy of the part, researchers Gowda et al. found that orienting an SLA printed part ninety degrees so that it was perpendicular to the original had an effect on the tensile and impact strength of the finished part (2014). Due to its effects in this manner it is included in the factors affecting print quality on an SLA device.

Similarly, in a study conducted by Puebla the orientation of an SLA print was tested to observe its impact on the mechanical properties of the part. Puebla printed standard parts for mechanical testing in two batches, the first had parts laying flat, on their side, and repeated this at ninety and forty-five degrees. The second consisted of all parts on the same angle but alternated from lying flat, on
its side, and completely vertical (2009). Puebla found that the mechanical properties were different among the different orientations.

In a recent study conducted by Zhang et al. the orientation of printed parts was altered in order to determine their effect on dimensional accuracy of geometrically complex parts (2016). Zhang et al. devised a method for determining the optimal print orientation by creating an equation that combines multiple print properties and determines which is the best option for production (Zhang et al., 2016).

**Material Change.** Material change is another factor that plays a role in the dimensional accuracy of an SLA printed part. Material change refers to the difference in material properties of photopolymer resins used in the SLA process and their impact on SLA print quality. Three studies are reviewed in this section to demonstrate the effect of material change on the SLA process.

Skliutas et al. conducted a study and showed that material change had an impact on the resolution of printed parts (2017). Their findings concluded that different materials had varying effects on final products. This means that using different materials had varying effects on wall-width production, in this case for biological purposes (Skliutas et al., 2017). These findings show that by changing the material there is an effect on dimensional accuracy.

In a study conducted by Weng et al. SLA photopolymer resin was modified and tested against other resins for its effect on the accuracy of an SLA printed part (2016). Weng et al. found that by adding nanoparticles to SLA photopolymer
resin that the finished part had different properties. The part was tested for its mechanical properties as well as its dimensional accuracy for five different types of resin (2017). The study found that the tensile strength was affected greatly by changing the material and that the printed accuracy was not significantly influenced.

In a recent study conducted by Al-Imam et al. material change in an SLA device was examined for its effect on the accuracy of dental casts (2017). Al-Imam found differences in the accuracy of the cast made from two different SLA resins, although the one that had the lower accuracy was created using a smaller layer-thickness (2017).

Six factors, vat location (in x,y, and z direction), material change, layer thickness, and part orientation, will be studied in a screening experiment to understand their effects on the dimensional accuracy of an SLA printed test artifact. This study will employ the use of geometric element test target (GETT) to carry out the experiment.

**Additive Manufacturing (AM) Test Artifacts**

The use of test artifacts for 3D printing has been carried out by numerous researchers. (Moylan et al., 2012; Moylan et al., 2014; Li et al., 2016; Ostrout, 2015; Chang et al., 2015; Jared et al., 2014). These targets utilize geometric shapes and features to test the devices ability to accurately reproduce them. “A standardized test part can be used to quantitatively evaluate the performance of
a machine or process. The clear benefit of a standardized part is that different machines or processes that produce the same standardized part can be easily compared.” (Moylan et al., 2012). This addresses the need for test artifacts to not only assess one printer against another but to quantitatively establish the capabilities of any AM device.

**Previous Artifacts.** Bhushan et al. created a test artifact comprised of geometric shapes such as circles and squares in both the positive and negative direction (cut out of the part, and extruding from the part) (2000). The experiment aimed to identify the main factors contributing to the dimensional accuracy of SLA prints. Their study concluded that through the use of test artifacts layer thickness, overcuring, and blade gap had the largest affect on the dimensional accuracy of the printer.

In the studies conducted by Moylan et al., and Jared et al. complex test artifacts were designed to understand the capabilities of the AM devices. (2014; 2014). Moylan et al. created a complex test artifact comprised of a multitude of geometric shapes, angular, positive, and negative features as shown in Figure 5. The features on this artifact are as follows, pins and holes to determine displacement error as well as beam width. Staircases to determine the error of the machine to produce straight features parallel to the machine axes. Ramp, this feature is designed to force the machine into producing a visible stair-step effect which is based on the layer thickness of the device. Lateral features are used to
understand the ability of the device to produce 3D contours. Fine features are used to test how small of a feature the device can produce.

![Figure 5: Test artifact designed by Moylan et al. with many features to test AM device capabilities](image)

The test artifact shown in Figure 5 has different features to test how the device can replicate the design file. Each of these features are measured using a coordinate measuring machine (CMM) which tests part dimensional accuracy (Moylan et al., 2012).

The test artifacts designed by Jared et al. do not contain as many features as the Moylan artifact but serve a different purpose. The first Manhattan Structure (Jared et al., 2014) is a square shape comprised of smaller individual square columns at varying heights which is able to show the printers capability in the x, y, and z direction. The second is a polyhedron artifact with sixty-two sides to show how the device handles planes and edges at different angles and
orientations. The last artifact is an eight-sided Siemens star which shows the devices resolution capabilities. (Jared et al., 2014).

This research will focus on using test artifacts to assess the device’s dimensional accuracy. Recent research conducted by Ostrout utilized a test target comprised of lines with varying width to assess the dimensional accuracy of material extrusion AM devices (2015). The methodology used in this experiment is called GETT, which is a way of creating test artifacts to test the dimensional limitations of the AM device. The results of the experiment showed that the GETT methodology is a viable option for AM device assessment regarding dimensional accuracy. This was done by varying the factors of the experiment and analyzing their effects on the printing process.

**Geometric Element Test Target (GETT).** The GETT methodology is equated to test targets created for the two-dimensional printing industry in terms of visual inspection and measurement standards for quality control (Chang et al., 2015). This methodology is transferred into the AM industry by creating parts to test the geometric and dimensional viability of 3D printers (Chang et al., 2015).

The use of GETT in the additive manufacturing industry provides a standardization tool for benchmarking and appraising the quality of 3D printing devices (Chang et al., 2015). The GETT methodology implements the use of test artifacts of specific geometric orientation and size in order to test the limits of the device it is being manufactured on (Chang et al., 2015; Moylan et al., 2014). These artifacts are designed so that the printer fails in replicating the intended
design, and the capabilities of the process can be measured based on the factors used in the GETT artifact (Chang et al., 2015).

The research by Chang et al. utilizes two different fused deposition modeling devices to test the GETTs artifacts and the printers’ ability to reproduce them (2015). The experiment used four different types of test artifacts, checkerboard, slanted ray, concentric circle, and flat ray as shown in Figure 6.

Figure 6: (a) Checkerboard, (b) Flat Ray, (c) Slanted Ray, (d) Concentric Circle GETT respectively. Reprinted with permission from “Geometric Element Test Targets for Visual Inference of a Printer's Dimension Limitations” S. Chang, H. Li, N. Ostrout, and M. Jhuria, 2015.

The results show the areas of device failure and how the GETT artifacts were able to exploit those weaknesses. This allowed the researchers to
benchmark each of the printers’ dimensional capabilities which serves as a metric for quality and process control of 3D printing (Chang et al., 2015).

**Experimental Design and Analysis**

The use of experimental design is illustrated in many studies with regard to 3D printing and dimensional accuracy. Numerous studies have been conducted that utilize a factorial design of experiment for the dimensional accuracy of AM test artifacts (Zhou et al., 2000; Chiu et al., 2015; Campanelli et al., 2007; Luthria, 2012). It is necessary to utilize this type of experimental design because of the many factors that accompany AM processes. These experimental designs contain both design and process parameters for factorial evaluation.

**Design of Experiments.** In an experiment conducted by Zhou et al. a Taguchi experimental design was used (2000). The experiment involved the optimization of the stereolithography process for dimensional accuracy which includes many factors such as layer thickness, overcure, hatch spacing, blade gap, vat position, exposure time, and recoat time. Due to the number of factors a full factorial approach would require 243 runs at three levels per factor. Instead, a fractional factorial approach was used which reduced the number of necessary runs to twenty-seven while still providing statistically significant results (Zhou et al., 2000). The design of this experiment allowed
Zhou et al. to draw conclusions of the factors affecting dimensional accuracy of printed parts in an efficient manner.

In an experiment conducted by Chiu et al. a fractional factorial design of experiments was used to test the significant factors that affect dimensional repeatability of SLA prints (2015). The design of this fractional factorial consists of five factors, (curing time, stable time, deep dip height, light flux, and platform moving velocity). It is a two-level experiment with a resolution of five (Chiu et al., 2015). The prescribed resolution means that a total of thirty-two runs need to be completed for meaningful results. Due to this design Chiu et al. were able to determine the significant factors with main effects on the finished product (2015).

Campanelli et al. conducted an experiment with a factorial design to optimize the stereolithography process for high precision applications (2007). The design utilized a fractional factorial design with three factors (hatch overcure, border overcure, and hatch spacing) at three levels apiece. The results of this experiment showed the optimal settings for a specific SLA device by varying the previously mentioned factors (Campanelli et al., 2007). Use of a fractional factorial design was paramount in this experiment because it reduced the number of runs required thus saving material and time.

In the experiment conducted by Luthria, a full factorial design was used with three factors, two of these factors had three levels, and one factor had four levels (2012). The test artifact consisted of slots positioned at different
angles illustrated in Figure 7. In this study the factors and levels affected only the design of the part including, slot angle, width, and layer thickness of features on the part shown in Figure 7. There was no change to the process parameters. Due to the design of the experiment the researcher was able to determine which combination of factors and levels had the largest influence on print quality of the test artifact. The experimental design helped to develop a better understanding of the individual factors and their effect on dimensional accuracy of the printed part.

![Figure 7: Representation of the test artifact designed by Luthria (2012)](image)

Similarly, a factorial design was utilized in the study conducted by Ostrout. The experiment consisted of three factors at two levels each. The test artifact in this study is a line GETT consisting of three sets of three lines protruding from the printed piece, each set varied in width which can be seen in Figure 8 (2015). The factors of this experimental design considered the process parameters while keeping the design of the test artifact constant.
Through this experiment Ostrout was able to find the settings for an FDM device that result in optimum print quality (2015).

![GETT target designed by Ostrout. Reprinted with permission from “Quantifying a fused deposition modeling system’s dimensional performance through its addressability” N. Ostrout, 2015.](image)

The use of a factorial design of experiments is demonstrated in the previously discussed studies. Using a factorial design to assess AM processes is a very efficient method compared to other experimental designs mentioned in previous chapters. The ability of the factorial design to reduce the number of runs necessary while providing significant information about the factors being tested as illustrated in this section. Due to the number of factors
In the SLA print process, it is shown that the use of a fractional factorial design is an efficient and statistically significant method of experimentation.

**Graphical Analysis.** The analysis portion of this experiment will employ the use of a visual/graphical analysis methodology, GETT, illustrated through research done by Li (2016).

Li uses the GETT methodology to evaluate 3D printed test targets for the printers’ resolution. The GETT targets are created in a way to induce dimensional failures so that they can be visually assessed using graphical analysis. Li used two different graphical analysis tools to find the forbidden zone, and wedge angle of the ray GETT used in the experiment. These values were then used to find the minimal producible width of the printer (Li, 2016).

This idea can be applied to any type of experiment, in this case it will be used to compare a 3D printed test artifact with its original CAD file to see the differences in the print and where the printer struggles. The use of graphical analysis will circumvent the need to use cumbersome and time consuming machinery such as a coordinate measuring machine (CMM) to observe the test artifacts creating a more practical and efficient method for device evaluation.
Conclusion

This review of the literature began with identifying key factors of SLA dimensional accuracy and how other studies show these factors' affect on the quality of SLA parts. Due to their relevance to the SLA process, spatial location, part orientation, slice thickness, and material change, they are the six factors that will be examined in this thesis. Following the factors affecting print quality, this review of the literature examines the use of test artifacts in order to test these factors. The literature shows that the use of test artifacts is ubiquitous among other researchers who are experimenting with the dimensional accuracy of 3D printed parts and thus make it a good fit.

The use of factorial experimental designs for experiments involving AM devices has been reviewed in this chapter. Factorial experimental designs are efficient and effective in determining relationships between multiple factors within an experiment. This was shown by the studies done by Luthria, Ostrout, Zhou et al., Chiu et al., and Campanelli et al. who were able to construct experiments with multiple factors and levels to yield meaningful results in an efficient and effective manner. The analysis of this experiment will be done using graphical analysis. An example of graphical analysis use in the GETT methodology has been researched and shown. The literature review shows that the use of graphical analysis provides an intuitive way to examine and make inferences on the data.
Chapter 4: Research Objectives

The goal of this research is to identify the main effect factors among the six that play a role in a stereolithographic device in terms of dimensional changes and spatial variation. This study will analyze both process and design factors of a stereolithography 3D printer and their impact on dimensional accuracy. Vat position, in the x-y-z direction, and GETT orientation are four design factors that are controlled before the print begins. Material change, and slice thickness are inherent to the SLA device and are the two factors of the process that are changed. This research will examine these six factors in order to answer these research questions:

1. Is the z-directional addressability of the SLA device affected with respect to the six factors, if so which are main effects?
2. Is the x-y resolution of the SLA device affected by the six factors, if so which are main effects?
Chapter 5: Methodology

This research discusses the changes in spatial variation of 3D printers. This is done through the use of Geometric Element Test Target (GETT) test artifacts which are constructed to test the limits of the device. Through the use of GETT, true resolution and addressability are able to be determined by measuring the features and failed areas of the GETT artifact.

This experiment used GETT artifacts to test the spatial variation of stereolithography (SLA) 3D printers. This means that the GETT artifact was positioned at a certain height above the build platform. This was carried out using a design of experiment called a factorial design. Using GETT artifacts and a factorial design six factors were tested for their effect on the quality of parts printed on an SLA device.

The methodology of this experiment is discussed in this chapter. The experiment consisted of six factors, x, y, z-location, GETT orientation, slice thickness, and material change, and two responses, minimal producible width (x-y resolution) and addressability (z-directional addressability). The method in which each of these factors were created and how the responses were measured are included in this section.

The methodology of this experiment begins with the computer aided design (CAD) file creation and dimensions of the test artifact to show how it was designed with specific parameters for the GETT methodology. Following the
Solidworks overview an explanation of the experimental design for this particular experiment is discussed to demonstrate how the experiment was conducted and the outline it followed. This section will conclude with a look into the printing procedure for the Form 2 SLA device and the graphical analysis technique used for data collection.

Design of the Experiment

In order to address the research objectives a fractional factorial design of experiment with a resolution of IV was adopted. Shown in Table 2 the design of this experiment is $2^{k-2}$ with “k” being the number of factors in the experiment, six, at two levels apiece. The design was repeated four times with a total number of 64 runs.

Table 2

<table>
<thead>
<tr>
<th>Experimental Design for this Experiment</th>
<th>Full $2^k$</th>
<th>Fractional $2^{k-p}$</th>
<th>This Experiment $2^{k-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>k: Number of Factors</td>
<td>6</td>
<td>6</td>
<td>64</td>
</tr>
<tr>
<td>Number of Runs</td>
<td>64</td>
<td>16 (IV)</td>
<td>64</td>
</tr>
<tr>
<td>Number of Repeats in the Experiment</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

The six factors are as follows, x, y, and z positions on the print bed, slice thickness, GETT orientation, and material change shown in Figure 10 below. The
factors used in this experiment were put into the Minitab software and the design it created designated the order and combination of factors and levels for the experiment. Each run consisted of four test artifacts in predetermined positions equidistant from each other in a grid, the height variation of the artifact occurred in the same position.

Figure 9: Fish-bone diagram of the experimental design including the factors for this experiment

The nature of this particular SLA device created problems in the original experimental design with regard to material change, slice thickness, and dimensionality. First, the material change and slice height cannot vary within a single run, this is due to the nature of the device and is unavoidable. Second, in each position there can only be one height, for example if an artifact is printed in a position on the print bed a second one cannot be printed in the same position.
with a different z-value. This will alter the artifacts from the intended design and obscure the results, therefore this had to be changed so that no artifact shared the same position but different z-values per run.

The experiment was run according to the design created in Minitab with the exceptions mentioned previously. The design of this experiment is shown in the appendix.

**X, Y, Z-Location**

The .stl file was then loaded into the software, Preform prefers to orient the figure itself to optimize the printing process however this takes away from the experiment and thus its recommendation was ignored. The GETT targets were oriented in a 2x2 grid according to the positions and orientations in the x-y plane prescribed by the experimental design which is shown in Figure 10. Figure 11 shows the difference z-position for the experiment prescribed by the design.
Figure 10: Representation of the positions of the GETT targets on the print bed according to the experimental design. The layout of GETT artifacts in Preform with measurements between the targets and their x-y location with regard to the experimental design are shown above.
**GETT Orientation**

Two orientations of the GETT were created. The first orientation has the 1mm height ray at 0, 90, 180, and 270 degrees and the 2mm height ray at 45, 135, 225, and 315 degrees. The other rays are evenly distributed throughout the GETT in an alternating pattern. The second orientation is the opposite of the first with the 2mm height ray at 90° and the 1mm height GETT at 45°. These specific parameters were put into the Solidworks software to create the test artifact as shown in Figure 12.
Figure 12: Left) GETT orientation 0 Right) GETT orientation 1. Notice the difference between 0 and 1, the rays at the 90-degree marks relative to the fiducial marks, alternate heights between 1 and 2mm.

**Slice Thickness Material Change**

The SLA device being used is a Formlab Form 2™ SLA device which uses a laser to cure one spot of photopolymer resin at a time. The printing process begins by converting the Solidworks file into a stereolithography file type (.stl.), this is done by choosing “save as” and selecting .stl as the file type. The .stl file is then uploaded into the print driver software Preform™.

The Preform software is a product of Formlabs as well and is made to work with their printing devices, the Form 2™ for example. Before the .stl file is loaded into Preform the user must define what resin and resolution is being used, this experiment used the “Tough” and “Grey” resins at a layer thickness of 0.05mm and 0.1mm which is shown in Figure 13.
Design of a Two-Height Slanted Ray GETT

Solidworks was used to design the test artifact for this experiment. It allows the user to define precise dimensions for the artifact which is important so that testing can be done on whether the printer can achieve these dimensions. The design of this artifact is a two-height slanted ray GETT with the maximum height at the outer edge alternating between 1 and 2 mm and going to a height of zero at the center.

The artifact base has dimensions of 1in x 1in x 0.15in. Each ray is an isosceles triangle with dimensions of 0.45in x 0.59in, the ray needed to be constructed with these dimensions so that the area between the rays equals the area taken up by the rays. This means that each ray occupies 7.5° of the GETT.

Figure 14 shows the GETT from two different angles.
Print Procedure

Fabrication of the 3D printed sample begins with the CAD software Solidworks (SW), from which a digital file of the target was created. The file was uploaded into the printer software where groups of four test targets were printed at a time. The parameters of the printer and the test target were arranged according to the experimental design. Once the test targets were situated in the software they were printed using a Formlab Form 2.

Once the design of the print is finished the user sends it to the printing device, in this case the Form 2, making sure the bed is clean and the resin cartridge vent is open before sending. The Form 2 has an automatic resin filling feature which allows for a clean and hands-free use of the device and resin changing. The printer will then heat the resin to 31°C and then the print will begin automatically.

Figure 14: a) top view of the slanted ray GETT showing the convergence of each ray to the center. b) angled view of the slanted ray GETT showing the varying height of each ray.
Finishing the print is very straightforward, after the print is finished the bed is taken off of the device and the GETT targets are gently removed. It is important to be gentle while removing the targets so as to not damage or warp the finished product. The targets are then transferred to an isopropyl alcohol (IPA) bath for one to two hours where any excess resin is dissolved. The prints can then be removed and dried off with compressed air and labelled for analysis. When changing material it is necessary to switch the resin cartridge and tanks with the new material and wipe down the bed with a microfiber cloth and a light IPA rinse. This print process was carried out for 64 samples for a total of 16 runs, 64 total targets, 4 targets per run. The sample artifacts were printed using a Formlab Form 2 SLA printer. Once the array was printed it was photographed and stored for image analysis.

**Graphical Analysis**

Image analysis on printer quality and process control was done after the sample was documented. Images of the printed GETT were overlaid with two different graphical analysis tools, one which measured the angle of each ray and the other which measured the diameter of the minimal producible width. The x-y resolution was determined by finding the minimal producible width according to the formula in Figure 15. Once the resolution was found for each GETT the results were compared to the varying factors in the design.
Width of Ray at Failure = \( \sin\left(\frac{\text{Wedge Angle}}{2}\right) \times \text{Diameter} \)

Figure 15: Formula for calculating minimal producible width, diameter equal to the diameter at the center of the ray GETT which the printer was unable to resolve.

In order to find the wedge angle of the GETT target the graphical analysis grid consisted of a CAD drawing with rays separated by 3°. Figure 16 shows how this grid was overlaid onto an image of the GETT, and how the wedge angle was then estimated based on the grids’ fit to the actual target. Similarly, in Figure 17, to find the minimal producible width, a CAD drawing of concentric circles with a diameter starting at 0.6mm and increasing by 0.2 mm to 2.0mm was used to estimate the forbidden zone diameter. The grid was laid over the image of the GETT artifact and the diameter was estimated using the graphical aid.
Figure 16: A graphical grid was designed and overlaid onto an image of the test target. Each section of the grid is three degrees. Therefore, from the images the wedge angle of the test target can be easily estimated.

Figure 17: The image on the left shows is that the printing device is unable to reproduce certain features and that these defects can be measured. The image on the right shows the graphical grid used to estimate the diameter of failure.
Data analysis was done in Minitab to construct an ANOVA table to interpret the data. The measured variables in this experiment are wedge angle, diameter of failure, wedge height, and the number of steps per wedge. The wedge angle and diameter of failure were both found using the graphical analysis tools mentioned previously. The wedge height was measured using a caliper and the number of steps per wedge were counted using a zoomed image of the test targets. From these four variables the response variables could be calculated.

The response variables for this experiment are the addressability of the 1 and 2mm ray heights (z-directional addressability) and the minimal producible widths for the 1 and 2mm ray heights (x-y resolution).
Chapter 6: Results

The experiment, described in the methodology, produced a large amount of data which has been collated and organized according to the experimental design by the researcher in Minitab statistical software. This section will present the results from the experiment with regard to each factors’ role in the process.

Analysis of the Variance (ANOVA)

An ANOVA test was run on the response variables to understand any correlation between the factors and the responses. During this test a p-value of less than 0.05 shows that the null hypothesis can be rejected and the alternate hypothesis can be accepted. The terms within the ANOVA are as follows, degrees of freedom, adjusted sum of squares, adjusted mean square, F-value, and P-value. ANOVA tests for each of the responses will be shown in the following sections to identify the main effect factors.

Response Variable: Minimal Producible Width 2mm Ray Heights

The first response variable being examined in this section is the minimal producible width of the device, or in other words the x-y resolution, this is the smallest width that the printer is able to produce under the set conditions with respect to the six factors of the experiment. The ANOVA test shown in Table 3 illustrates that the main effect of this response variable is the material change
factor with a p-value of 0.002 in Table 2. The x and y position had the second greatest impacts on the x-y resolution with p-values of 0.377 and 0.352 respectively. This means that the change of material had the largest impact on the minimal producible width of the test artifacts in this experiment.

Table 3

ANOVA Results for Response Variable Minimal Producible Width 2mm

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1</td>
<td>0.000206</td>
<td>0.000206</td>
<td>0.79</td>
<td>0.377</td>
</tr>
<tr>
<td>Y</td>
<td>1</td>
<td>0.000230</td>
<td>0.000230</td>
<td>0.88</td>
<td>0.352</td>
</tr>
<tr>
<td>Z</td>
<td>1</td>
<td>0.000101</td>
<td>0.000101</td>
<td>0.39</td>
<td>0.536</td>
</tr>
<tr>
<td>Slice Thickness</td>
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<td>0.000000</td>
<td>0.00</td>
<td>0.976</td>
</tr>
<tr>
<td>Material Change</td>
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<td>0.002659</td>
<td>0.002659</td>
<td>10.20</td>
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</tr>
<tr>
<td>GETT Orientation</td>
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<td>0.000016</td>
<td>0.000016</td>
<td>0.06</td>
<td>0.803</td>
</tr>
<tr>
<td>Error</td>
<td>57</td>
<td>0.014859</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>63</td>
<td>0.018071</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 18 confirms a normal distribution of the data for the response variable Minimal Producible Width based on the evidence provided in the four plots. This is true because in the normal probability plot the data fits the straight line with little variance. The histogram is relatively normal and indicates that the data is not biased. The data points in the versus fits plot are randomly scattered about zero and lastly the versus order plot shows no pattern in the data. The results of these residual plots from the ANOVA test can confirm the normal distribution and validity of the data for the response variable ‘Minimal Producible Width (2mm)’.
The response variable examined in this section is the Minimal Producible Width of the 1mm height wedges on the GETT target. Table 4 shows the results of an ANOVA test of the data for response variable Minimal producible width 1mm. The material change factor had the lowest p-value, 0.000, indicating the largest effect on the response variable.
Figure 19 confirms a normal distribution of the data for the response variable Minimal Producible Width 1mm based on the evidence provided in the four plots. This is true because in the normal probability plot the data fits the straight line with a small amount of variation. The histogram shows a normal curve and indicates that the data is not biased. The data points in the versus fits plot are randomly scattered equally about zero and lastly the versus order plot shows no pattern in the data. The results of these residual plots from the ANOVA test can confirm the normal distribution and validity of the data for the response variable ‘Minimal Producible Width 1mm’.

Table 4

ANOVA Results for Response Variable Minimal Producible Width 1mm

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1</td>
<td>0.001693</td>
<td>0.001693</td>
<td>1.03</td>
<td>0.314</td>
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Figure 19: Residual plots for response variable: Minimal Producible Width 1mm Ray Heights

**Response Variable: Addressability 2mm (Step/mm)**

The response variable examined in this section is the Step Size of the 2mm height wedges on the GETT target. Table 5 shows the results of an ANOVA test of the data for response variable Step Size 2mm. The material change and slice thickness factor had the lowest p-values, 0.010 and 0.000 respectively, indicating the largest effects on the response variable.
Table 5

ANOVA Results for Response Variable Addressability 2mm (Step/mm)

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Figure 20 confirms a normal distribution of the data for the response variable Step Size 2mm based on the evidence provided in the four plots. This is true because in the normal probability plot the data fits the straight line with a small amount of variation. The histogram shows a normal curve and indicates that the data is not biased. The data points in the versus fits plot are randomly scattered equally about zero focused around two specific locations and lastly the versus order plot shows no pattern in the data. The results of these residual plots from the ANOVA test can confirm the normal distribution and validity of the data for the response variable: Step Size 2mm.
The response variable examined in this section is the Step Size of the 1mm height wedges on the GETT target. Table 6 shows the results of an ANOVA test of the data for response variable Step Size 1mm. The material change and slice thickness factor had the lowest p-values, <0.001 and <0.001 respectively, indicating the largest effects on the response variable.
Table 6

ANOVA Results for Response Variable Addressability 1mm (Step/mm)

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Figure 21 confirms a normal distribution of the data for the response variable Step Size 1mm based on the evidence provided in the four plots. This is true because in the normal probability plot the data fits the straight line with a small amount of variation. The histogram shows a normal curve and indicates that the data is not biased. The data points in the versus fits plot are randomly scattered equally about zero focused around two specific locations and lastly the versus order plot shows no pattern in the data. The results of these residual plots from the ANOVA test can confirm the normal distribution and validity of the data for the response variable: Step Size 1mm.
Figure 21: Residual Plots for Response Variable: Addressability 1mm (Step/mm)

**Main Effects Plots**

Figure 22 is a main effects plot of the six experimental factors on the response variable Minimal Producible Width 2mm. The vertical axis represents the mean values of the data in millimeters (mm), and the horizontal axis represents the level of each factor respectively. The x, y, and z location of the GETT artifact shows a moderate amount of deviation from the mean. The slice thickness and GETT orientation factors show the least amount of deviation from the mean indicating a small impact on the response. Material change shows the largest deviation from the mean between its two levels meaning that for this particular response variable it has the largest effect.
Figure 22: Main Effects Plot for Minimal Producible Width (2mm)

Figure 23 is a main effects plot of the six experimental factors on the response variable Minimal Producible Width 1mm. The vertical axis represents the mean values of the data in millimeters (mm), and the horizontal axis represents the level of each factor respectively. The x, y, and z location of the GETT artifact shows a moderate amount of deviation from the mean. The slice thickness and GETT orientation factors show the least amount of deviation from the mean indicating a small impact on the response. Material change shows the largest deviation from the mean between its two levels meaning that for this particular response variable it has the largest effect.
Figure 24 is a main effects plot of the six experimental factors on the response variable Addressability 2mm. The vertical axis represents the mean values of the data in steps/millimeter (mm), and the horizontal axis represents the level of each factor respectively. The x, y, and z location of the GETT artifact shows little deviation from the mean. The GETT orientation factor shows the least amount of deviation from the mean indicating a small impact on the response. Slice thickness shows the largest deviation from the mean between its two levels meaning that for this particular response variable it has the largest effect.
Figure 24: Main Effects Plot for Addressability 2mm (Steps/mm)

Figure 25 is a main effects plot of the six experimental factors on the response variable Addressability 1mm. The vertical axis represents the mean values of the data in steps/millimeter (mm), and the horizontal axis represents the level of each factor respectively. The x, y, and z location of the GETT artifact shows a small amount deviation from the mean. The GETT orientation factor shows the least amount of deviation from the mean indicating a small impact on the response. Slice thickness shows the largest deviation from the mean between its two levels meaning that for this particular response variable it has the largest effect.
Figure 25: Main Effects Plots for Addressability 1mm (Step/mm)
Chapter 7: Discussion and Conclusion

This chapter will discuss and analyze the results of the experiment and the implications of this thesis in the industry. It will begin with a characterization of the SLA process and follow with an analysis of the results from the previous chapter.

Discussion

Due to the nature of this experiment, the solidification of a photopolymer in a layer fashion, it is reasonable to expect a certain amount of variation in the data. Uncontrollable factors in this experiment could arise from ambient and photopolymer temperature fluctuations as well as over and under-cure of the resin by the laser. These factors are taken into account by the researcher when examining the data from the experiment.

The results from experiment showed that the material change factor had a large effect on all six responses, this is shown in the main effects plots and the ANOVA tables in the previous chapter. The p-values for minimal producible width 2mm, minimal producible width 1mm, addressability 2mm, and addressability 1mm were 0.002, <0.001, 0.001, and <0.001 respectively for the material change factor. The low p-values allow the researcher to reject the null hypothesis and accept the alternate. The slice thickness factor had low p-values for the responses addressability 1 and 2mm, <0.001 and <0.001 respectively. The other
factors did not appear to have an effect on the response variables due to the high p-values and low deviations in the main effects plots.

The influence of the material change factor is seen in all four response variables. The use of different materials as a factor for this experiment addresses the printer’s ability to resolve the CAD file to the input specifications. During this experiment both materials were used under the same parameters yet yielded the greatest effect on the responses. The effect could be due to the differing properties of each material which could affect the curing of the photopolymer resin. The two materials used, Formlab Grey (level 0) and Formlab Tough (level 1) photopolymer resins, could be affected differently by laser cure times or in other words the solidification of the resin could take a longer or shorter time depending on the material which could impact the responses in this experiment.

In addition to material change, the slice thickness factor also had a pronounced effect on the response variables addressability 1 and 2mm. Varying the slice thickness for a print is expected to show differences in the addressability of the device. In this case the expectation is that the addressability is exactly half for the two slice thicknesses.

The x, y, and z-location factors test the printers’ spatial variation in print quality for this experiment. In this experiment the x-location also showed an effect on the responses Addressability 1 and 2mm according to the pareto charts found in Appendix B. This could be due to the scanning pattern of the laser in the device, if it is continuously scanning one side before the other or the placement
of the laser is at a greater angle at the varying x-locations it could affect the dimensions of parts produced as the researcher observed in this experiment.

**Conclusion**

The intention of this Thesis is to bridge the GETT methodology from FDM into SLA and to use it to test the capabilities of an SLA device. 3D printing technology is rapidly influencing the manufacturing industry and a need for process control for these devices is essential for its success. This research examines the main effects on quality and dimensional accuracy with regard to six factors in the printing process.

The six factors that were researched and used in this experiment are as follows, x, y, and z location, material change, GETT orientation, and slice thickness. In order to conduct an experiment surrounding these SLA print factors a fractional factorial design was created in Minitab consisting of six factors at two levels apiece. The experiment was carried out and the results were analyzed.

The results of this experiment showed that material change had the largest effect on the response variable Minimal Producible Width 2mm. This is due to the low p-value, 0.002, found after conducting an ANOVA test on the data which means that the null hypothesis can be rejected. The response variables Addressability 1 and 2mm were affected by the material change and slice thickness factors the most. With p-values of <0.001 and <0.001 respectively for 1mm addressability and 0.001 and <0.001 respectively for 2mm addressability.
the null hypothesis can be rejected. The results show that material change has the largest effect on the resolution of the device and that slice thickness and x-location have the largest effect on device addressability.

This experiment addressed six factors which are important to the quality of parts produced by an SLA device. It demonstrates the viability of the GETT methodology for device assessment and builds upon previous GETT methodology work done on FDM devices and other studies conducted on SLA dimensional accuracy. This screening experiment shows the factors that are going to have the greatest effect on the dimensional accuracy of SLA printed parts. The researcher believes this experiment shed light on the factors affecting SLA print quality by using the GETT methodology and can be transferred to the AM industry for device assessment in an industrial setting.

**Future Research**

Due to the resources available for this experiment, the Form 2 SLA device does not have the ability to alter laser power or cure time, the researcher suggests that this experiment be run under the same principle but with these two factors added to the design. In addition, regarding the current experiment the researcher would use greater x, y, and z-location values to test the spatial variation to a larger extent.

**Validation Study.** In order to validate the experiment work needs to be done with a larger sample size to ensure the fidelity of the data. The six factors
and levels would remain the same and would allow for the results of this experiment to be verified.

**Study Using Different Factors.** This study utilized six factors, x, y, z-location, material change, GETT orientation, and slice thickness, that contribute to the accuracy of SLA printed parts. However, due to the limitations of the resources available other important factors to the SLA process were unable to be examined, these factors include laser power and cure time. Future work could replace the GETT orientation and material change factors on a different SLA device.

**Study of Larger Spatial Variation.** The x, y, and z-location factors in this experiment utilized a portion of the build plate, however the outer edges of the plate remain untested. Future research could observe the dimensional accuracy of the device with locations at a higher level of separation than conducted in this experiment.
Bibliography


Chung, Robert; Sigg, Franz; Ploumidis, Dimitrios; and Caruso, Doug, "Test Targets 6.0: A Collaborative effort exploring the use of scientific methods for color imaging and process control" (2006). Accessed from: [http://scholarworks.rit.edu/books/75](http://scholarworks.rit.edu/books/75)


Appendix A

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Appendix B

Pareto Charts for all Response Variables

Pareto Chart of the Standardized Effects
(response is Minimal Producible Width (2mm), \( \alpha = 0.05 \))

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Standardized Effect

Pareto Chart of the Standardized Effects
(response is Minimal Producible Width (1mm), \( \alpha = 0.05 \))

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Standardized Effect