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Factors Affecting Dimensional Precision of Consumer 3D Printing

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3D printing has been gaining more widespread usage, with falling prices and operational simplicity bringing the tool out of the realm of corporations and into the hands of individuals. Indeed, the techniques comprising today's rapid prototyping – creating full-scale models that reproduce the size, shape, and functionality of conventionally manufactured items – have made it possible for individuals to create new products in shorter timeframes than whole corporations could just a few short years ago. Roland DGA Corporation (2011) cites two major shifts in how products are developed – an economic shift caused by rising costs associated with outsourced manufacturing and an increase in entrepreneurship, respectively – which are pushing towards a business model where conceptualization and productization are co-located. Three-dimensional Computer-Aided Design (CAD) data and 3D scanning technology have both been made available and refined through open-source communities, in addition to the availability of their for-profit counterparts. The 3D printer forms the final component in a chain which turns ideas and intellectual property into tangible product.

Rapid prototyping expedites the typical manufacturing process through the use of both subtractive and additive technologies, as opposed to wholesale creation of customized tooling – the traditional approach (CustomPartNet, 2009). A subtractive technology, such as CNC milling, uses digital data to transform raw material by removing material in a predetermined fashion. By skipping the step of creating typical manufacturing tooling, the same rapid processes, techniques, and tools can be used to manufacture a wide-range of devices more quickly.

The most ubiquitous and economical consumer 3D printing devices make use of additive technology – fused deposition modeling (FDM). FDM builds up a physical model layer-by-layer, fusing higher layers of material to the layers beneath them to create new objects (Akande, 2015). Though the march towards increasingly capable consumer printing has been steady, it is important

to note that economical 3D printing devices have not yet achieved a level of simplicity and reliability comparable to that of the typical consumer devices that have achieved mass adoption. In order to provide a quantitative analysis of this reliability, the study described in this paper focused on dimensional precision of a consumer-grade, FDM printer. A full factorial design of experiments (DOE) analysis was conducted, resulting in an Analysis of Variance (ANOVA) design that shed light on the various factors that affect the use of FDM, in terms of dimensional precision. The goal was to evaluate the limitations of the technology, to rule out factors that do not contribute in a statistically significant fashion to print precision, and to provide a practical, quantitative guide for optimizing results of consumer grade 3D printing for application as an engineering tool.

Finite Deposition Modeling – An Emerging Technology

FDM raw material may consist of a variety of substances – often thermoplastics or thermoplastics infused with other materials. The most common materials used for FDM are Acrylonitrile butadiene styrene (ABS) and Polylactide (PLA), with their characteristics of becoming a liquid substance with predictable flow properties in response to heat, while forming a reliable solid once cooled (Liing Shian Colorant Manufacturer Co., Ltd., 2013). This process of heating and cooling plastic, with some well-modeled aspects, is still susceptible to random variation, with unpredictable results depending on the shape being printed. Differences in material properties across manufacturers and even across different material lots from the same manufacturer can result in very different printing results, requiring user intervention to refine several printer parameters until usable prints are achieved (Boots Industries, n.d.). These include extrusion rate, nozzle temperature, bed temperature and the properties of the design, itself. Several papers in the public literature (e.g., Bakar, Alkahari, & Boejang, 2010; Luzanin, Movrin, &

Plancak, 2013; Udroiu & Mihail, 2009) have attempted to quantify the effects of various user-controllable factors on print quality. In at least one case (Luzanin, 2013), the investigators were required to change their experimental plan when the printer was found to be incapable of printing adequate test articles.

The focus of this paper is on the use of consumer-grade 3D printing to create engineering prototypes of, tooling for, or finalized instances of mechanical devices. Unlike aesthetic uses of FDM, a focus on accuracy - ability to meet precise physical dimensions, consistent shapes, and predictable surface finish - is important in the case of engineered mechanical devices. 3D printing, because of its additive nature, provides a capability to create unique components that cannot be replicated via subtractive techniques. Consumer grade printing provides advantages in both expense and turnaround time that represent a significant change in how certain engineering challenges may be addressed. The measurement of fluid flow, for example, necessitates very precise control of dimensioned parts with specific characteristics (The American Society of Mechanical Engineers, 2004), which works counter to the concept of physical experimentation. The approach of using changeable, disposable components in order to iterate towards an optimal combination of test parameters, has previously been impractical. 3D printing could, among other uses, provide a way to fabricate customized fluid flow test components that rival their significantly more expensive and less-readily-manufactured (and, in turn, less practically customizable) metallic counterparts. In order to meet the requirements for such applications, however, consumer 3D printing must first attain a level of dimensional consistency and precision that is, as yet, atypical of FDM technology.

An example of the kinds of dimensional errors prevalent with consumer 3D printers is the problem of creating simple round pegs and mating holes. A fastener, intended to fit within a

cylinder is often found to not mate correctly, and attempts to introduce simple linear correction factors into slicer software have not been successful (Tmorris9, 2014). The positive-space peg often exceeds the dimensions specified, and the negative-space hole typically falls short of the guiding dimension. The two will not mate. Indeed, the use of non-3D-printed fasteners such as screws and bolts is often complicated by this failure to achieve an accurately dimensioned hole size. It should be understood that conventional finishing/machining techniques, such as drilling and sanding, are not always appropriate for a hollow-core, fused-layer part. Holes added after the fact can sometimes breach the component outer envelope, leaving the less-rigid inner honeycomb – a standard weight/cost savings feature – exposed. Also, sanding fused layers of plastic does not yield the same results with the same ease as can be expected with sanding a monolithic material. Lack of predictability with FDM prints poses a significant challenge.

The study described in this paper investigated the various factors that affect the use of PLA material with FDM, in terms of dimensional precision, to provide a quantitative guide for optimizing results of consumer grade 3D printing for use as an engineering tool. Moreover, many of the factors affecting print quality listed in the public literature do not appear to be based in a mechanical understanding of how the printer operates, but rather, inconclusive anecdotal evidence. I hypothesize that, once all confounding variables are accounted for, some of the oft-repeated causes of dimensional variation – print speed, shell thickness, and print size – will be shown not to be statistically significant contributors.

Method

3D printers have different make-up and functionality from one to the next. Consumer 3D printers, however, have some similarities in how they are constructed (France, 2013). They generally rely on some form of stepper-motor/belt drive system to move the print head in the x-y

axis, as material is expelled, forming the particular shape desired. Another stepper-motor, with some form of direct drive gear or threaded rod serves to raise and lower the print bed, creating the desired layering of material. Another motor with a tensioning/drive system is used to move raw material – in the form of a plastic filament – through the hot-end, which heats the material to a liquid state, before it is expelled through a precisely machined nozzle. In such a system, there are both theoretical device limitations on precision – motor step size, nozzle width, hot-end temperature sensor accuracy – as well as practical expectations for variation. Loose belts, inaccurate filament sizing, and nozzle clogging can all contribute to variation. It has even been reported that something as seemingly innocuous as the size and surface characteristics of a clear plastic Bowden tube in which the raw material travels before being liquified or the physical location of the material spool relative to the printer can introduce filament friction and flexing, resulting in print inaccuracies (Gr5, 2014, June 5; & Illuminarti, 2014, June 5). Inherent technological limits and the associated tradeoffs are what I sought to investigate.

There are many intangible factors, however, which influence how a final printed-object dimension deviates from the original CAD definition. The software used to define the object to be printed, for instance, can contribute error (Creastudiostore, 2014). Slicer software, which is used to convert the desired object into a layer-by-layer instruction set defining the toolpath which the printer follows, can generate different results from the same initial specifications. Similarly, default printer settings can fail to take into account the unique situations under which the print is being executed. I attempted to research all of these influences and to remove those which represented controllable variation in order to obtain a quantitative estimate of the dimensional precision of FDM technology.

Equipment and the Printing Toolchain

The printer used in this study was an Ultimaker 2 (Ultimaker B.V., 2015a), with PLA filament (nominal diameter, 2.85 mm). The printer is capable of manufacturing objects with a build volume of 223 x 223 x 205 mm, using a layer resolution of as high as 0.06 mm. It is capable of laying down material as fast as 300 mm/s, and it makes use of a heated print bed. Many features of the printer – from the precise width of the filament to the tension under which that filament is pushed through the system to the temperature of the hot-end/nozzle to the precise zero height of the center, left, and right sides of the bed – are user-adjustable. This makes for a significant number of variables to consider in optimizing output, before considering the slicer software specifically designed to work with the printer, named Cura. The Cura interface allows users to preview the simulated results of a print, layer-by-layer, as well as providing over 50 user-definable parameters that control the print. Many of these are not categorical parameters, but require specific decimal values. In the absence of fully understanding how many of these parameters affect the print, the new user is advised simply to accept the default settings (Ultimaker B.V., 2015b). I discovered through analysis, however, that some of these settings can directly introduce dimensional inaccuracy, depending on the nature of the print. These settings are not unique to this particular software/printer combination.

The CAD software used to develop the test articles for this study was CATIA V5R21. CATIA is a feature-based, fully associative CAD application (Dassault Systemes, 2013). This means that all models are generated with an inherent framework for subsequent applications in engineering analysis or machining. The method of creating the model is stored within the model itself. As model features are updated by the user, the associative nature of the application

correspondingly updates the steps for creating the model, so that this information is always represented and accurate.

With 3D printing, it is currently standard practice to use a Standard Tessellation Language, (.stl) file to store model information. As explained by Burns (1993/2015), "An StL ('StereoLithography') file is a triangular representation of a 3-dimensional surface geometry. The surface is tessellated or broken down logically into a series of small triangles (facets). Each facet is described by a perpendicular direction and three points representing the vertices (corners) of the triangle" (para. 3). Because the standardized format of an .stl file contains basic information about the envelope of the model and its shape, but not the way it is built, there is a conversion process that takes place through the printing toolchain. In the case of the Ultimaker 2, the CATIA model, with precision as accurate as the user desires – the default being six decimal places in whichever units the user prefers - is first converted to an .stl file which can have variable levels of precision. This .stl file is then imported into CURA, where it is manipulated into a toolpath specific to the Ultimaker printer – literally cartesian x, y, z coordinates for the print head to move, along with extrusion commands which tell the printer how much filament to unspool into the hot-end. These instructions are formatted in a standardized g-code file which is used by machine tools around the world. The opportunity for errors and inaccuracy arises each time a conversion takes place.

With so many different parameters affecting prints, it is impractical to conduct a quantitative study without limiting the scope of our analysis. After surveying several previous studies on 3D printing quality (Akande, 2015; Bakar, et al., 2010; Luzanin, et al., 2013; Udroiu & Mihail, 2009), I compiled a list of the key factors which those authors had concluded had the most significant effect on the quality and dimensional accuracy of prints. I added to that list parameters that my knowledge of the construction of the printer led me to believe could also affect the print.

The factors initially considered, in no particular order, are listed here: printing multiple model envelopes on the same bed at one time; stl file tessellation precision; desired dimensions incompatible with layer height or wall thickness settings; printing speed (which can be subdivided into several different types of movement: print head travel speed between extrusions, bottom layer speed, infill speed, top layer speed, outer shell speed, inner shell speed); extrusion rate adjustments (or printer material thickness settings) and maximum speed of deposition; differences between slicers' toolpath algorithms; rate of change of acceleration (jerk) required by the print, which is a function of shape; layer thickness; print fill density; overall size of the print; cooling fan interaction with the print; and shell thickness.

Ruling Out Print Error and Inherent Toolchain Inaccuracy

Through trial and error, in setting up the experimental study, several direct contributors to dimensional inaccuracy were identified and effectively removed from influencing the final data set. This also allowed for a reduction in the number of factors considered as part of the quantitative study. Each of those potential influences which were mitigated are addressed in this section.

The bottom layer of a 3D print, which directly contacts the print bed and serves as the base for the layers above is an important contributor to dimensional inaccuracy that can be resolved. If the bottom layer does not appropriately adhere to the print bed, the cooling process and material shrinkage in layers above it will tend to pull at the smallest features, with the least surface area in contact with the bed, causing sections of the print to warp. Sharp corners at the bottom of the print pose a particular problem. I found that a layer of kapton tape or blue painter's tape on the print bed, together with the heated bed of the Ultimaker 2 and chamfering the sharp corners of areas in contact with the bed made for a print that did not warp and was, moreover, so well attached as to make removal difficult. Typically, the surface in contact with the print bed is the most uniform,

not exhibiting the ridges associated with z-axis movement and forming a glazed surface due to contact with the heated bed. I did find, however, that there was significant deformation and inaccuracy in the first few layers of my prints, irrespective of the type of material used or the bed temperature selected. There was an apparent melting of the material on the bed, such that it always exceeded the outer desired envelope by approximately 0.5 mm, as illustrated in Figure 1.
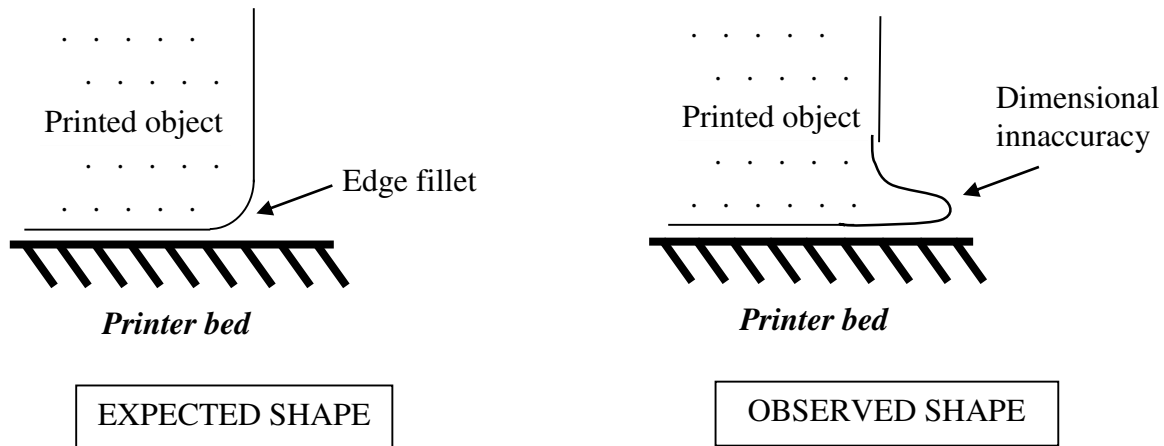

Figure 1. Graphical illustration of printer bottom layer inaccuracy.

This observation led to an analysis of the g-code file itself, deconstructing the x, y, z positional commands and the extrusion requests. I found that Cura's "advanced" settings allow for definition of an initial layer thickness and extrusion percentage. The print nozzle is raised from the surface of the bed by an amount greater than the standard layer height and uses greater-than-typical material flow, allowing for non-uniformity in the bed and also to ensure proper adhesion. By putting a simple circle and square shape through the slicer and analyzing the resultant g-code, it was clear that with user changes to these parameters, the cartesian coordinates are changed to compensate. An increased line width in the initial layer results in greater extrusion and in moving the positional data for the print head to compensate for the increased thickness of the initial lines, irrespective of the intended shape, which is cut-off at that initial layer height. It became obvious

that what seemed like a problem with material cooling and deformation had little to do with the material. The printer setting for filament material thickness, which is used to ensure a consistent extrusion rate, was actually being overridden by this additional factor in the Cura software, as was the intended filleted shape.

Even with optimal leveling of the print bed – a critical component of quality prints – minor variations in the bed and resulting differences in nozzle height from the bed for the initial layer will affect the width of the material flowing from the nozzle. Raise the nozzle higher, and the printed line becomes thinner. Press the nozzle closer to the surface, and the width of lines expands. It was found by trial and error that the extrusion settings needed for the initial layer could differ from subsequent layers by as much as a factor of two, in creating the same printed line width. While trial and error with the Cura settings can alleviate this dimensional inaccuracy, creating a raft for all the test articles – a solid piece of printed material on which the actual desired print rests, raised off the bed – ensured that this particular source of dimensional inaccuracy did not play a role in the study measurements.

In analyzing the coordinate information in the g-code provided to the printer, with the simple circle and square shapes, I also ruled out variation between the CAD dimensions and the printer toolpath. Exporting from CAD to an .stl file involves a process of tessellation – representing the shape using triangles - which can have varying precision. I found that with CATIA, there is a setting for "3D Accuracy" which can be set between 0.01 and 10.00. This value is hidden to all but the most astute user, and it does not affect either the displayed CAD model or any of the standard file formats. Even saving a .stl file will not reveal any variation due to this parameter. If, however, we save an .stl file and then import the file back into CATIA, we can see a marked effect from these parameter settings, as shown in Figure 2. The effect of this differing tessellation

precision would be to create approximations of curves with differing levels of precision, resulting in measured dimensional inaccuracy. Consider the case of an octagon representing a circle. Depending on where a measurement of diameter is taken, the result will vary from that of a uniform circle. Setting "3D Accuracy" to 0.01 ensured that tessellation inaccuracy did not play a role in the study.

Early prints showed that an additional source of dimensional variation was rooted in the physical dimensions of the printer and the discrete amounts of material that it is designed to extrude. Creating an object with a z-axis dimension that is not a multiple of the selected layer height can introduce dimensional error. Analysis of the g-code output from Cura demonstrates that the z-axis position of the print head does not match the desired dimensions when they are not a multiple of the selected layer height. The software does not attempt to extrude fractional layers in order to maintain accuracy. Similarly, the nozzle width of 0.4 mm limits the dimension of our horizontal shell thickness. These width and height constraints prevent the extrusion of excess PLA material which can create dimensional errors – attempting, for instance, to print two lines in the same physical space. The constraints create dimensional variation of their own, however, by not printing precisely what the user requests. The user needs to understand the limitations of the printer. The smallest layer height for deposition on the Ultimaker 2 is 0.06 mm, and all prints for this study were created with this layering resolution. Because the z-axis mechanism of the printer differs from the x and y axes, and because the z-resolution is smaller by nearly a factor of ten than the 0.4 mm horizontal line thickness, and because the z-axis movement is relatively slow and unidirectional (one step per printed layer) I focus exclusively on x and y dimensions in this study. Optimization in the z dimension is left as an exercise for a future investigation.
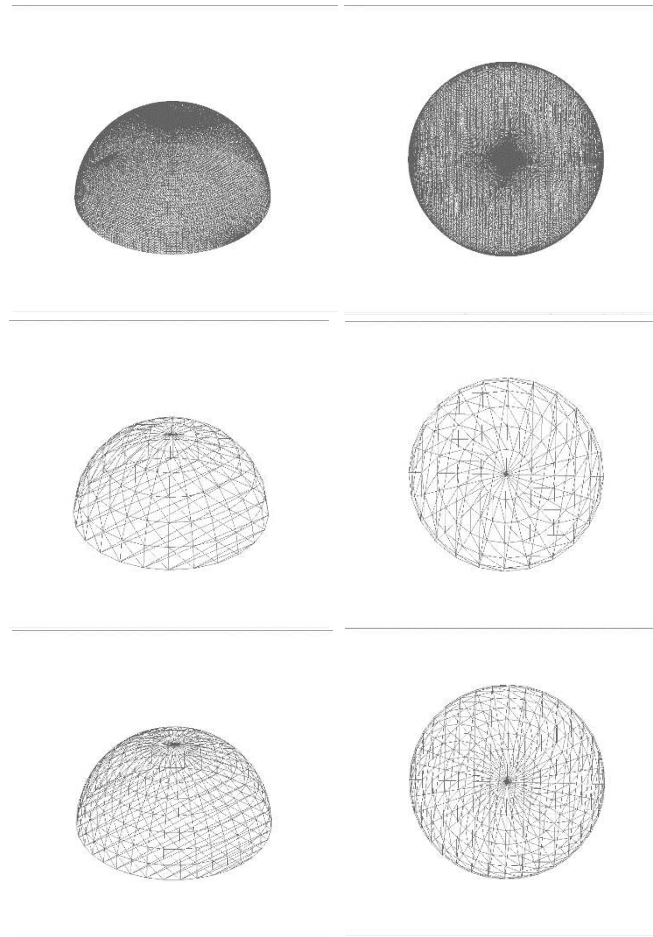
Figure 2. Isometric (left) and top orthographic (right) views of half sphere exported to .stl file with different tessellation settings (top to bottom image variation). Dimensional accuracy is compromised by the different quantity of lines used to represent the shape, resulting in an increasingly imperfect approximation of the curved surface.

Extrusion rate and its relationship to the speed of the print head – literally, the volume of plastic material which the hot-end is able to deposit in order to keep up with the movements of the print head – is listed in the public literature as a factor in print quality. Underextrusion – the failure to deliver sufficient material to maintain printing – can be detrimental to quality and accuracy, but it often prevents completion of prints at all. Figure 3 demonstrates a print with an infill setting of 20%, which was suffering from underextrusion.
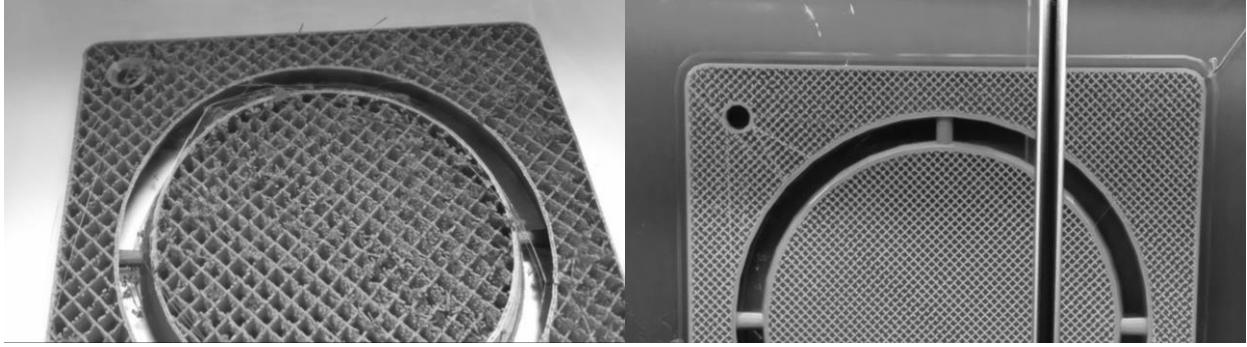
Figure 3. The differences between the image at left, exhibiting poor, frayed extrusion characteristics and the image at right, with crisp infill, are related merely to an increase in infill percentage. The right image, though printed at a denser infill rate, used a pattern which exhibited less jerking motion, allowing for more consistent adhesion between layers, resulting in a cleaner print.

Counterintuitive as it may seem, increasing from 20 to 25% infill – actually increasing the amount of material the printer must deposit – can help alleviate extrusion problems. In the case of Figure 3, the increase to 25% resulted in the printer using a different printing pattern. Rather than attempting to make several ninety-degree turns to create a cross-hatched pattern, box-by-box, the printer laid down straight lines across the full length of the print. By alternating the direction of these layers of parallel lines, the printer created the same cross hatch pattern with minimal extrusion problems. Extrusion issues stem from a combination of print head motion and inability to deposit material quickly enough. The tell-tale frayed lines visible in the left image of Figure 3 are all but eradicated from the right image of the same figure.

It should be understood that extrusion rate is generally considered as a threshold factor. Below this threshold – a certain volume of material per unit time – extrusion rate should not pose an issue to quality (Illuminarti, 2014, Jan 17), as demonstrated in Figure 4. For most functional prints, the motion and jerk exhibited by the print head is not within user control. It is best simply to leave a wide margin for error, such that the maximum extrusion capability of the printer is not

exceeded. This margin is sometimes overlooked, because extrusion rate margin results in longer duration prints.
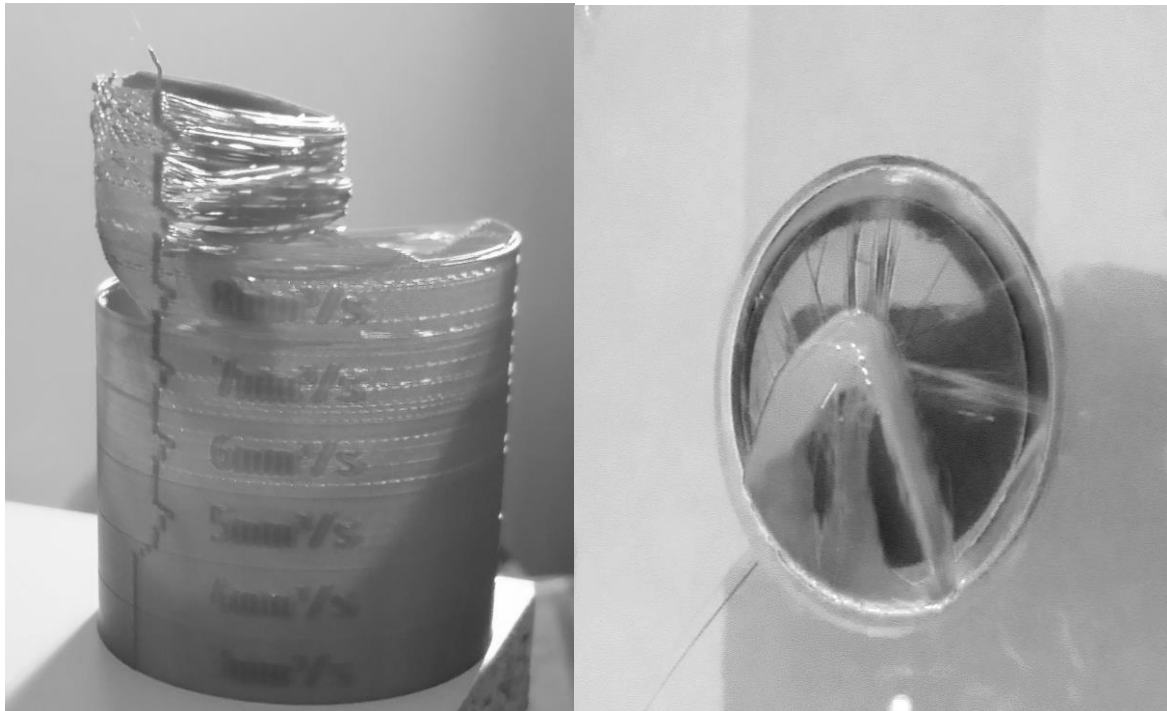

Figure 4. Author's print of Illuminarti extrusion test – front (left) and top (right) views – demonstrating that as extrusion speed increases, the printer has difficulty maintaining the outflow sufficient to fuse to the lower adjacent layer while maintaining circular motion. Past a threshold of ~8 mm^3/second, the motion of the printer hot-end pulls the plastic away from the intended circular path. Above ~5 mm^3/second light ca be seen shining between some poorly deposited layers.

For purposes of this study, it was possible to optimize the repetitive printing of test articles such that jerk is not believed to have played a significant role. A single instance of apparent error due to jerk, as shown in Figure 5, could be accounted for and ruled out by changing the way infill was applied. Cura maintains settings for "infill overlap %" – how far over the innermost line of the print shell or outer print envelope the infill is allowed to overlap. It should be noted that it may be possible for future implementations of slicer software to account for jerk, in creating the printer toolpath, and to limit movements such that they do not detrimentally affect print quality.
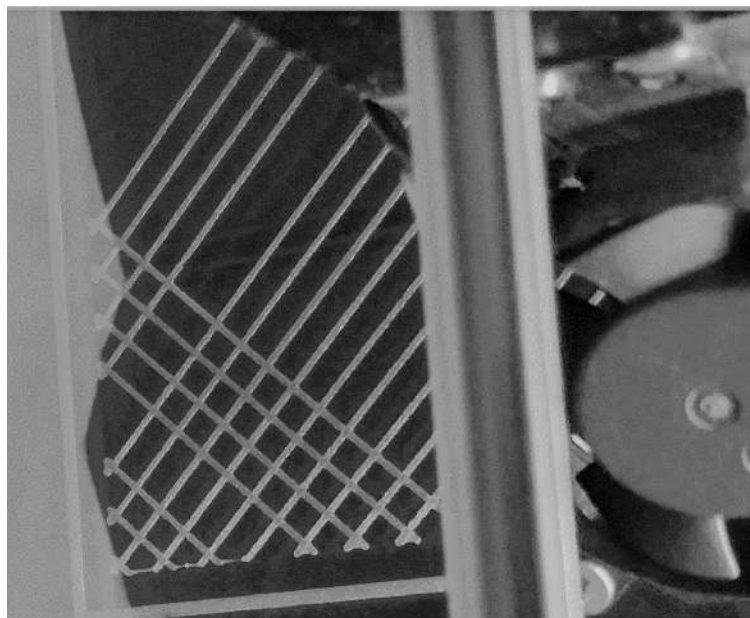
Tight change in direction visibly flings material rather than typical deposition edge of print
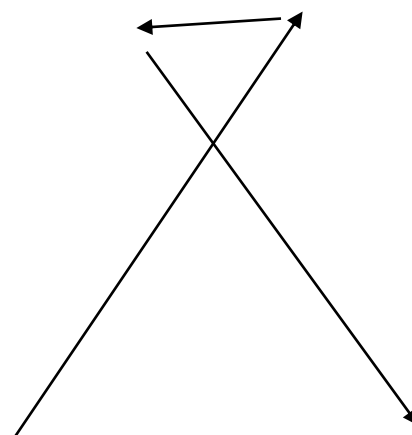
Figure 5 – Evidence of the potential detrimental effect of too high print head jerk. Because of how infill cross hatch pattern is positioned relative to the envelope of the print towards the bottom of the image, it necessitates a significant change in acceleration forces, causing material to build up on the edge.

From Table 2, the highest speed attained during extrusion maneuvers – actual deposition of material – was 50 mm/sec. Since the printer nozzle diameter is 0.4 mm, the area of the nozzle is Pi*(diameter/2)^2 = 0.126 mm^2. Multiplying area of the nozzle by the speed of the nozzle movement yields a maximal extrusion rate of 6.28 mm^3/sec, which is within the capabilities of the Ultimaker 2, as demonstrated in Figure 4.

Finally, certain types of prints will necessitate lifting and moving the print head after printing the current layer or feature. During these moves, it is possible that additional material is released or dropped unintentionally in a region of the print. In order to prevent this, Cura allows users to make use of a feature called retraction. From France 2013,

Retraction… will greatly improve the quality of your prints. By retracting the hot

filament with the extruder motor during travel moves, plastic oozing is prevented. The

length of filament to retract before moving to the next extrusion path will depend wildly

on the motor and gearing you have… Extra length on restart is the length of plastic you'd like to extrude after traveling to a new path and prior to moving again… The only application for this may be when your extruder has serious problems starting up again after retraction… (pp 42-43).

In order to prevent the dimensional errors that could occur because of the retraction of filament and the need to restart between layers – re-priming the nozzle – this feature was disabled for the test articles, in favor of combing. From Ultimaker B.V. (2015c): "Combing is the act of avoiding holes in the print for the head to travel over. If combing is 'Off' the printer head moves straight from the start point to the end point and it will always retract." Retraction and the associated nozzle re-priming, then, was removed as a source of dimensional imprecision.

Design of Experiments

In order to evaluate the effect of the factors selected as well as any interaction effects between these factors, it was decided that a DOE approach would be conducted with two levels associated with each factor. In creating physical test articles, we are limited by the printer size, by material expenditures, and by the time duration required to print the test articles. With the Ultimaker's performance specifications, some simple 5x5x5 inch prints can take over thirty hours to print at the fastest settings. Also, occasional failed prints can necessitate a restart, wasting that significant print time. Size and speed settings were selected such that the longest test article print required ten hours.

Procedure

A full factorial DOE approach was selected with replication factor of sixteen – creating more than one sample data point in each treatment group - in order to maximize the information that could be extracted about interaction effects and to improve the accuracy in each selected

treatment group. Using a full factorial design, it is a relatively simple matter to analyze main effects and interactions effects. The balanced nature of a full factorial design is such that for any factor setting, there are an equal number of data points for all settings of all other factors, such that the effects of individual factors can be isolated by averaging over all other effects. The same holds for interactions between factors.

Hypothesizing that there may be some inherent error in the way the printer prints different shapes, positive versus negative space, or multiple components in a single print, it was appropriate to create test articles that yielded samples of different types of physical configurations. While even two samples from the smallest print exhibited reasonable physical separation and variation, it should be noted that all samples are not strictly independent. Measuring in multiple places on the same print opens up the possibility of some correlation between samples. At ten hours per print, with N = 128, printing each sample independently was impractical. If this study reveals statistically significant factors, a further decomposition of those particular factors with greater sample collection can be performed as part of a more targeted future study. Each test article was designed to yield sixteen measurement samples.

Test articles were printed in a random sequence to limit the effect of extraneous factors. With ANOVA testing, it is customary to calculate the power of the study as a method of selecting sample size. For a full factorial DOE, however, it is only possible to estimate power *a priori* (Ruttimann & Wegener, 2015). With multiple measurements taken from different areas of each test article in this study, there is added complexity in any power calculation. Since the practical capabilities to print more test articles was a limiting factor, I considered the Mee, R.W. (2009) recommendation of ten samples per treatment group in order to account for within run variation, and I decided upon sixteen observations per treatment group.
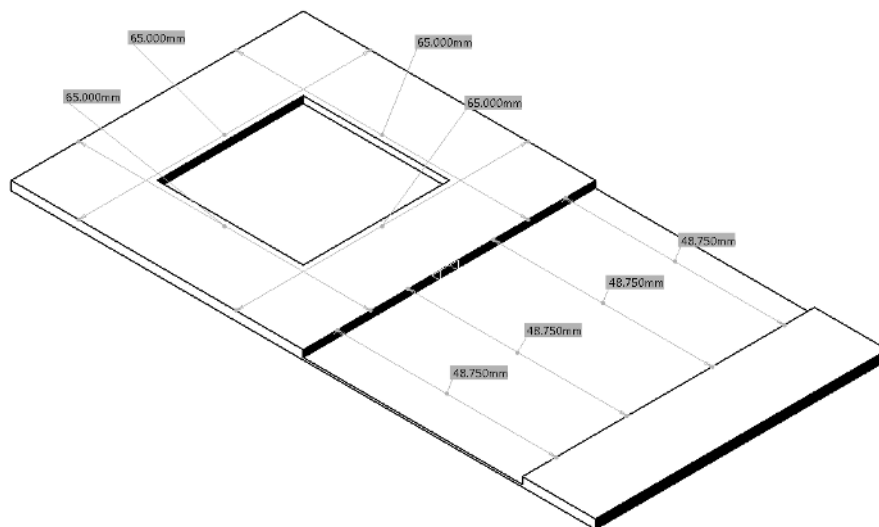
Figure 6. Isometric view of large square-shaped test article with measurement point locations for outer square and thickness of gap to adjacent rectangle
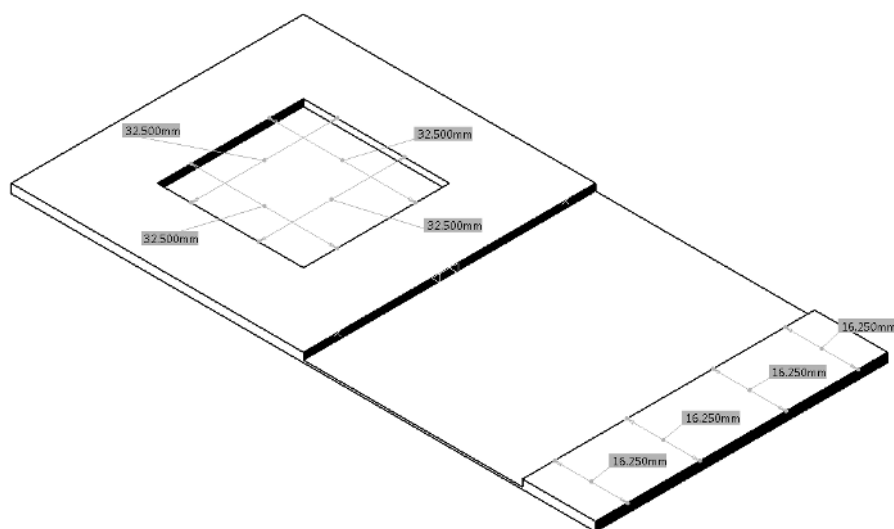

Figure 7. Isometric view of large square-shaped test article with measurement point locations for inner square and thickness of adjacent rectangle
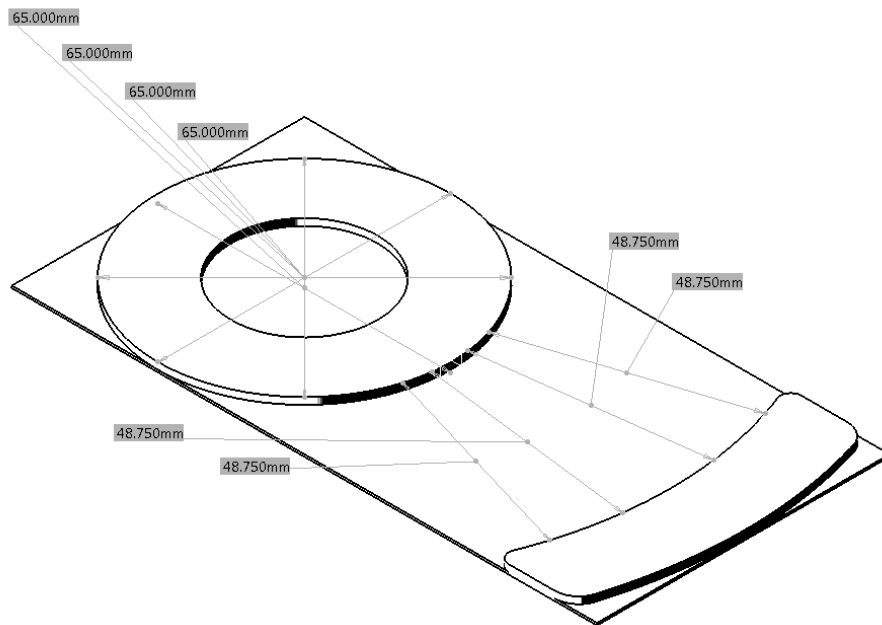
Figure 8. Isometric view of large circular-shaped test article with measurement point locations for outer circle and thickness of gap to adjacent arc

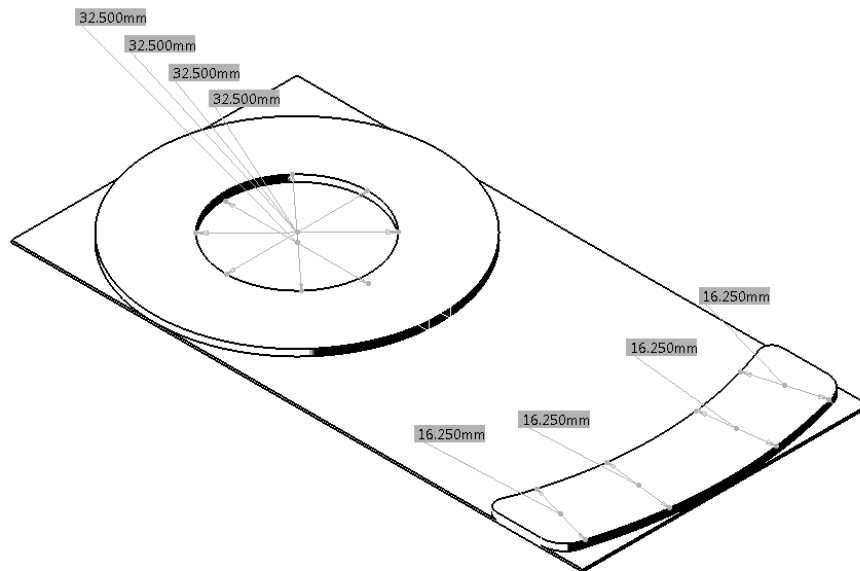*Figure 9.* Isometric view of large circular-shaped test article with measurement point locations for inner circle and thickness of adjacent arc

Since my approach is not, in point of fact, seeking to find a statistically significant effect as an academic exercise, but rather to optimize our use of a practical technology, the concern that this study might misclassify a factor which could have otherwise been viewed as statistically

significant (Type II error) is mitigated by calculation of p-values for each factor and the interactions between factors. Despite my use of the standard alpha = 0.05, it is possible for us to note factors that show a relatively low probability of occurring randomly and, as mentioned previously, future studies can make use of larger numbers of samples targeted to the particular factor in question to increase power. This approach allowed me to maintain sample sizes that are practical.

Table 1

Relevant Specifications for Mitutoyo CD-6" CS Digital Caliper

Resolution	0.01 mm
Accuracy	+/- 0.02 mm
Repeatability	0.01 mm

Dimensional data was obtained by direct measurement with an m-type vernier digital caliper – model Mitutoyo CD-6" CS with key specifications as listed in Table 1. In order to minimize measurement error in the $N = 128$ data points, a consistent procedure was used with only one operator capturing all data points, consistent with the best practices for accurate, repeatable measurement as outlined in Juran (2010).

Table 2 lists the various levels of factor settings used in my DOE analysis.

Since the dimensions the printer is expected to reproduce vary in scale, and with any known fixed bias removed from influencing data, it was appropriate to work with dimensional deviation as a percentage of the expected original dimension rather than simply a fixed dimension. The measured dimension on the test article, the fixed deviation from expected original, and the percentage error (positive for enlargement or negative for reduction in sizes) were captured for each of the $N = 128$ samples. From this point forward, however, this paper will address the percentage dimensional error values, unless otherwise noted.

Table 2

Low and High Settings for Test Article Printing

	Cura Descriptor	**Low (0)**	**High (1)**	**Units**
Speed	Print Speed	12.5	50 (400% speed of low test article)	mm/s
	Travel Speed	25	100	mm/s
	Bottom layer speed	5	20	mm/s
	Infill speed	10	40	mm/s, Cura calculates the ratio of this to "Print Speed" to set infill speeds (Illuminarti, 2013)
	Top/bottom speed	3.75	15	mm/s
	Outer shell speed	7.5	30	mm/s
	Inner shell speed	7.5	30	mm/s
Size	N/A	40 x 20	130 x 65 (325% size of low test article in each dimension)	mm
Shell	Shell Thickness	0.4	1.6	mm
Additional Relevant Settings	Layer Height	0.06	0.06	mm
	Top/Bottom Thickness	0.12	0.12	mm
	Fill Density	25	25	%
	Enable Combing	All	All	N/A
	Fan full on at height	0.5	0.5	mm
	Fan speed	100	100	%
	Infill overlap	15	15	%

Figure 10 is a graphical representation of the factor level settings for each of the eight experimental treatment groups.
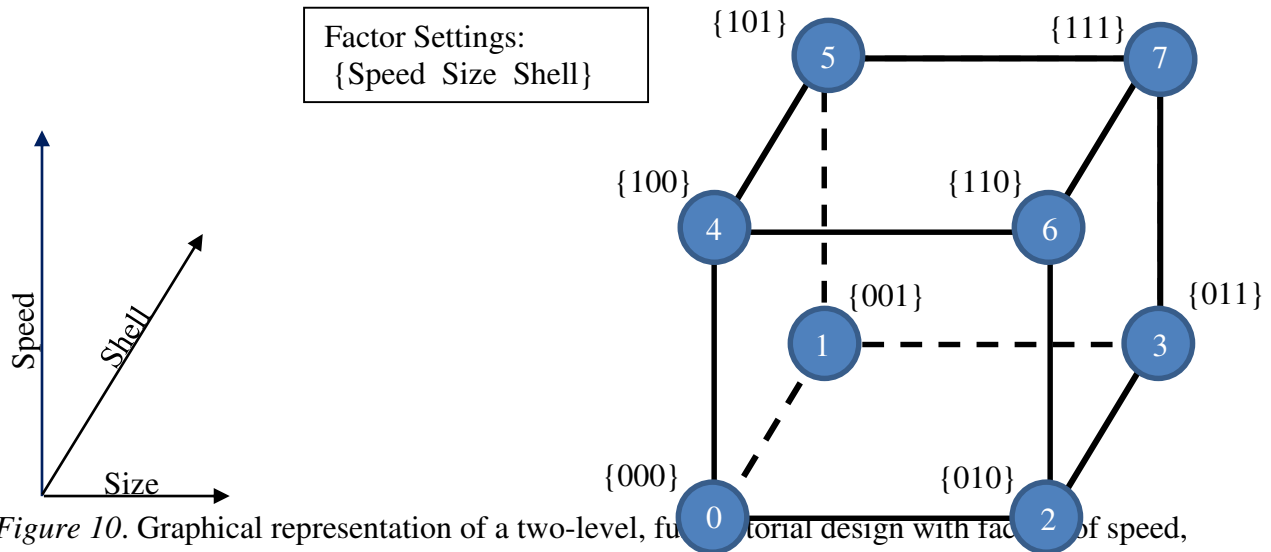

Figure 10. Graphical representation of a two-level, full factorial design with factors of speed, size, and shell thickness. Numbers in circles are base ten representations of the binary number formed from the concatenated factor level selections; arrows show the direction of increase of the factors.

Results

Square Test Articles

The square test articles were printed and corresponding data collected. Using the full factorial data, it is possible to construct plots of main effects, provided in Figure 11. The main effects demonstrate the trends in the mean percentage dimensional deviation data as the factors of print speed, shell thickness, and test article size were varied. These trend lines represent the effects of the factors in isolation.
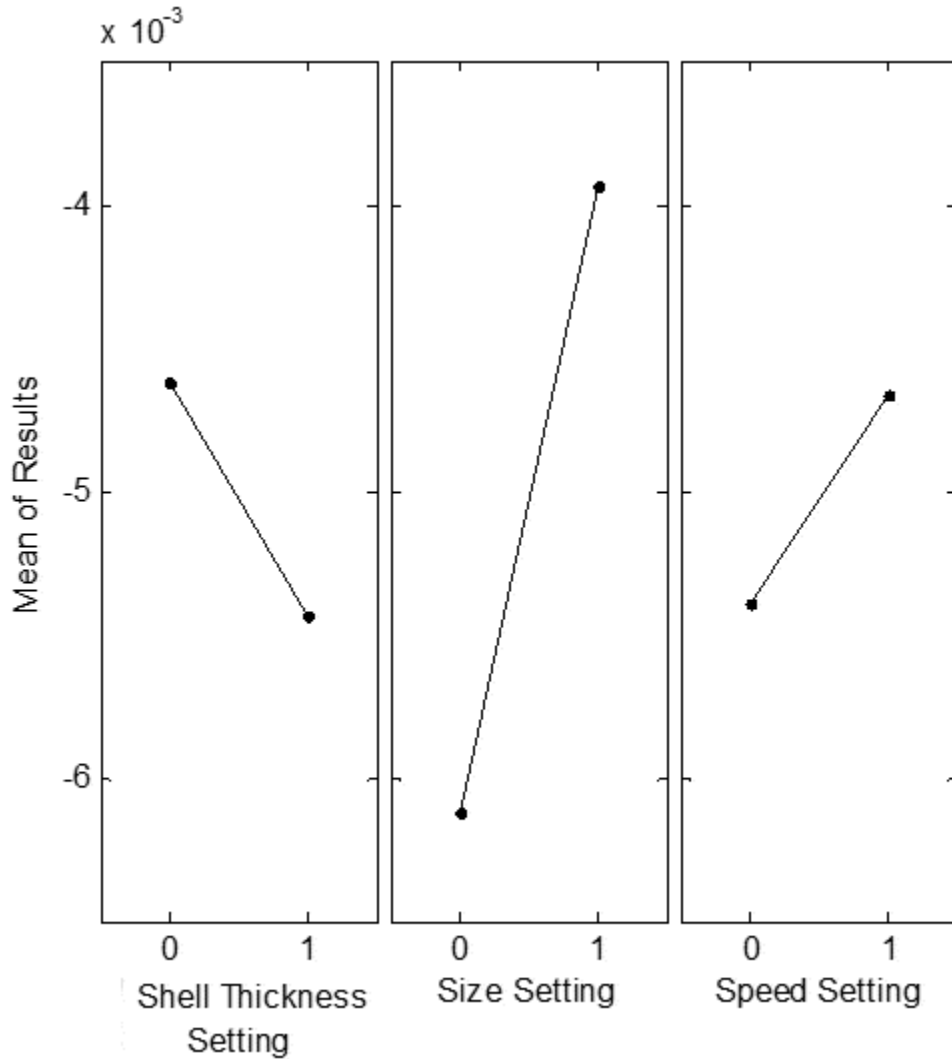
Figure 11. Main effects plots for square test article.

With the results of the design of experiments revealed, an ANOVA analysis can further elucidate which respective main and interaction effects are statistically significant. This analysis begins with testing the necessary assumptions and conditions that make the analysis valid. Grace-Martin (2012, May) provided guidance on the appropriate testing of assumptions for experiments similar to my full factorial DOE with eight treatment groups. For the square test articles, a Kolmogorov-Smirnov test was applied to the percentage dimensional error data. Across all N data points for the square test articles, the mean percentage error was -0.387% ($SD = 0.559$). Calculating

the z scores within each of the eight treatment groups – $z = (X - M_i) / s_i$, where the subscript i

denotes a statistic for the treatment group i – the eight resultant z vectors were each subjected to

the Kolmogorov-Smirnov test. The hypothesis is that the vector, z, comes from a standard normal

distribution at the 5% significance level. The test validated my hypothesis across all treatment
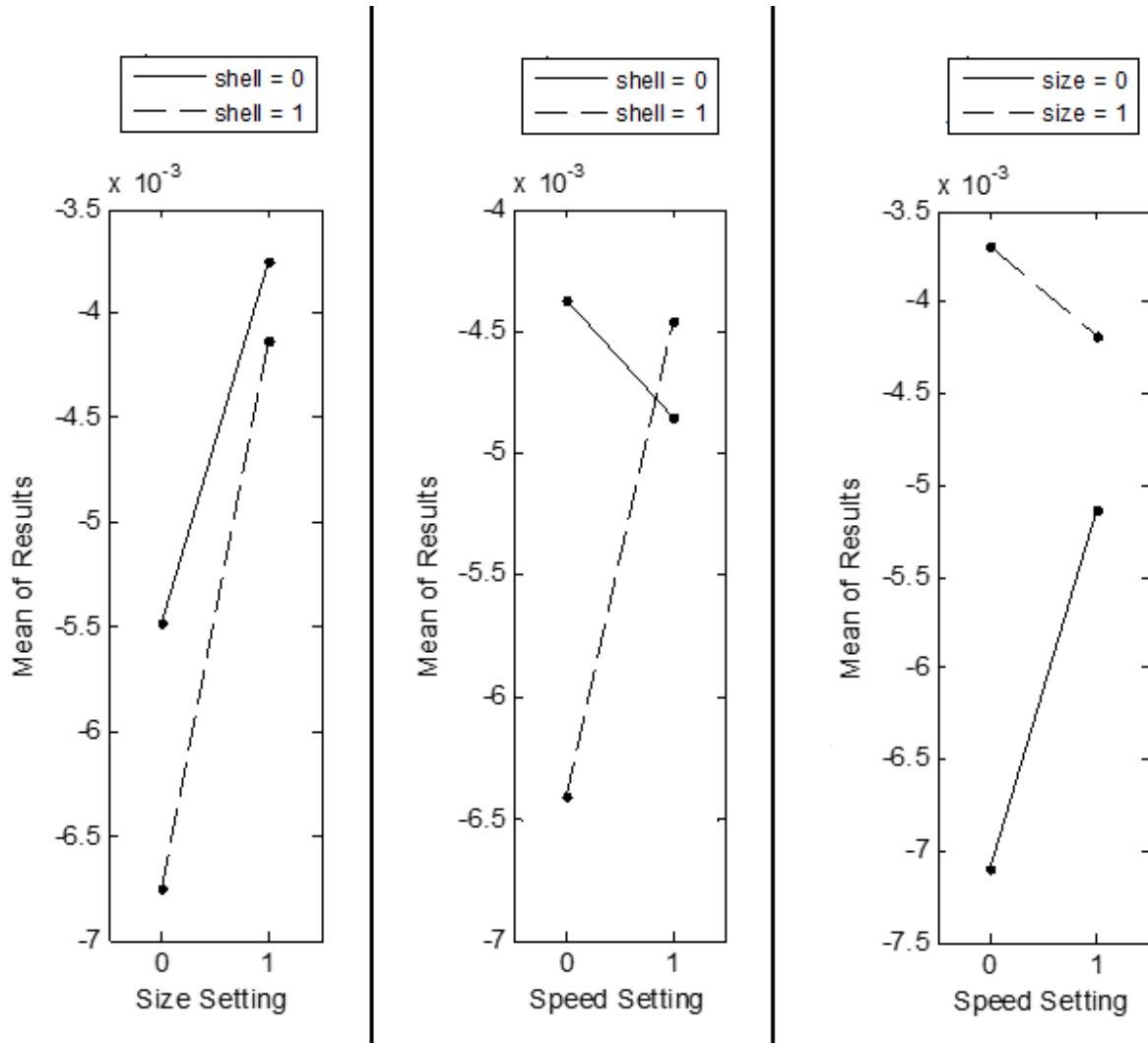
groups.

Figure 12. Interaction effects plots for square test article.

Because the data set is relatively large, by the central limit theorem, the data is sufficiently

normal to apply further statistical analysis with the assumption of normality, but the empirical

testing above was performed for completeness. Figure 13 is a plots of the empirical cumulative

distribution function obtained from the $N = 128$ data points, using the overall mean and standard deviation of the samples to normalize and provide a visual comparison to the standard normal curve.
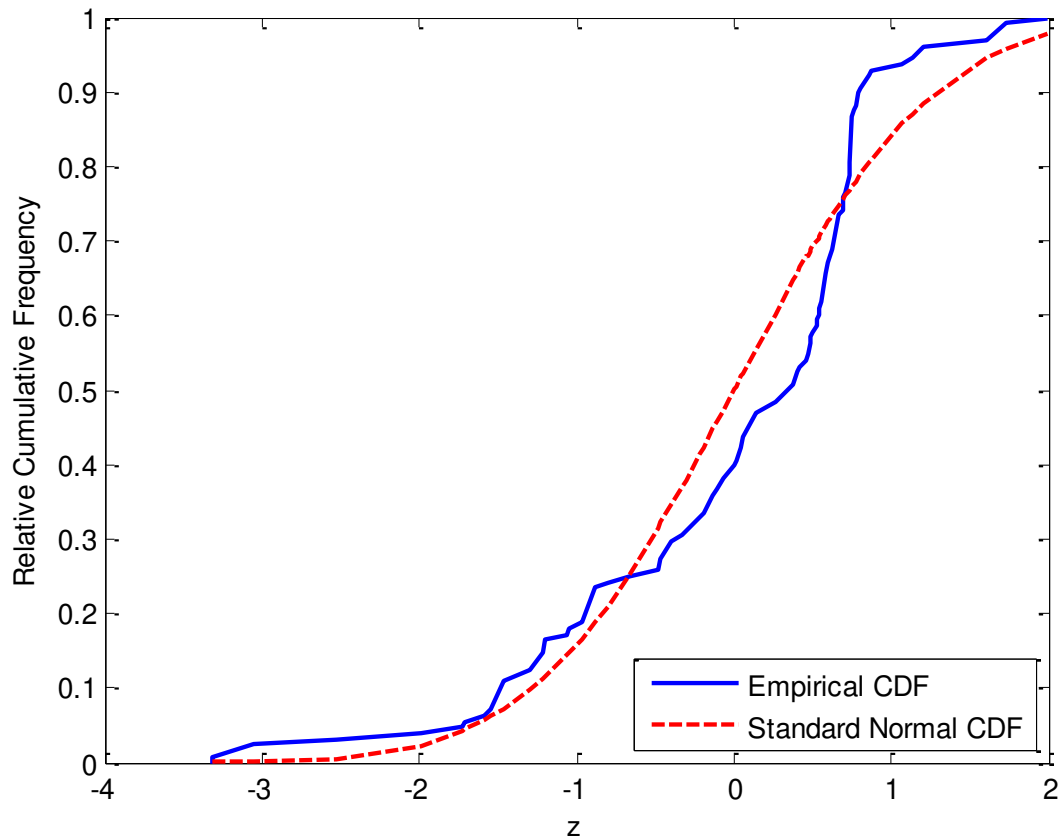
Figure 13. Plot of the overall empirical cumulative distribution function (CDF) of z-values for all square test article percentage deviation sample data (all treatment groups combined) from the square test article versus a standard normal CDF for visual comparison of normality.

The ANOVA analysis (results in Table 3) revealed that none of the main or interaction effects observed were statistically significant. The p-value closest to the selected alpha = 0.05 corresponded to the size factor, with an approximately 10% probability that the observed differences between treatment groups were due to random chance.

Table 3

Three-Way Analysis of Variance of Factors Affecting Dimensional Percentage Deviation in Square Test Articles

Source	df	SS	MS	F	p
speed	1	0.00002	0.00002	0.30	0.584
size	1	0.00015	0.00015	2.64	0.107
shell	1	0.00002	0.00002	0.38	0.541
speed * size	1	0.00005	0.00005	0.85	0.359
speed * shell	1	0.00005	0.00005	0.82	0.367
size * shell	1	0.00001	0.00001	0.11	0.743
Error	121	0.00694	0.00006		
Total	127	0.00724			

Circular Test Articles

The circular test articles were printed and corresponding data collected. Using the full factorial data, it is possible to construct plots of main effects, provided in Figure 14. Across all N data points for the circular test articles, the mean percentage error was -0.573% (*SD* = 0.607).
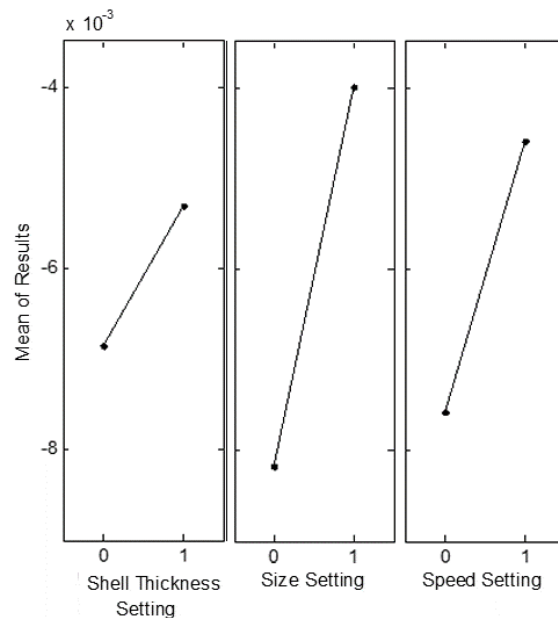

Figure 14. Main effects plots for circular test article.
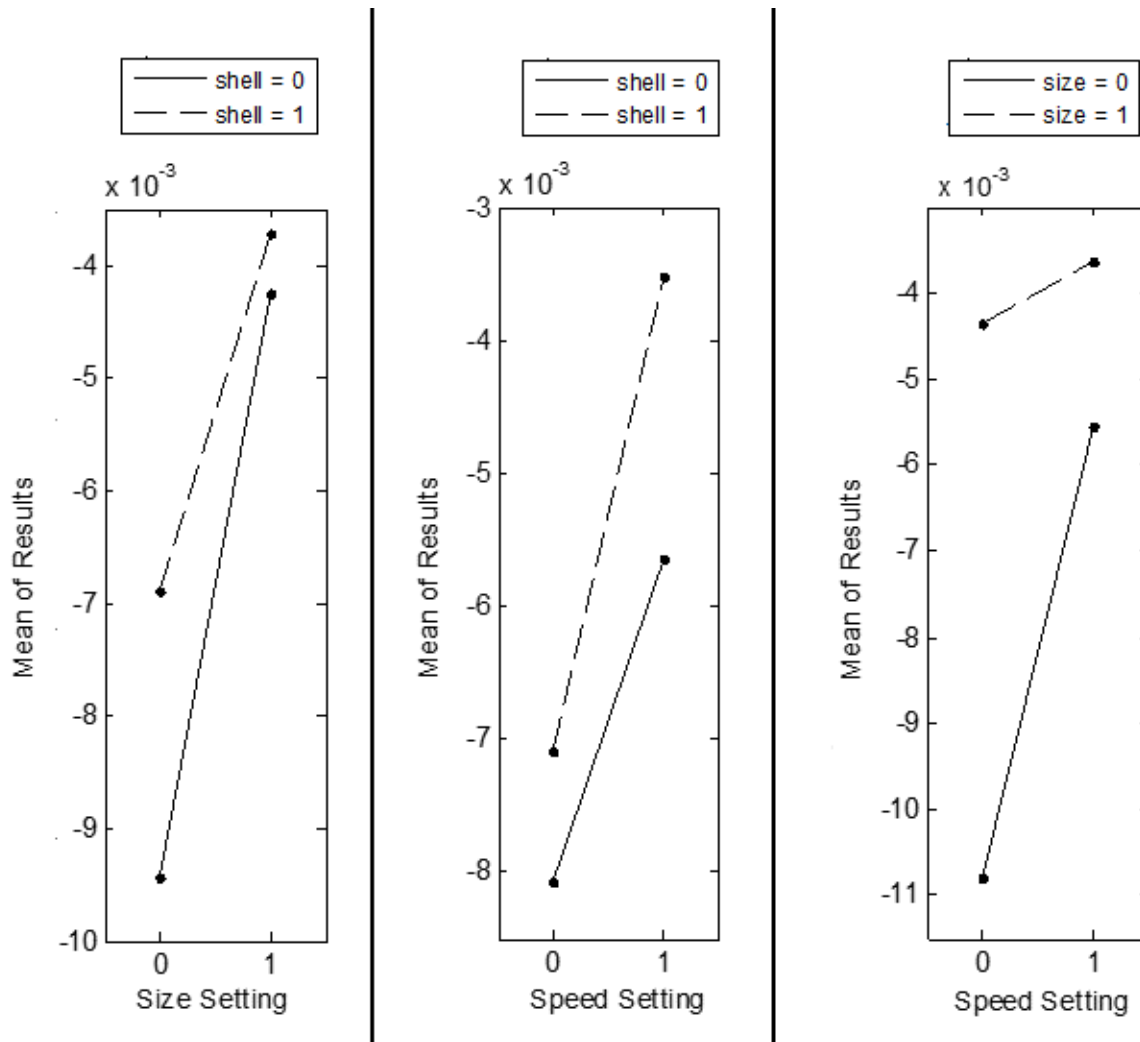
Figure 15. Interaction effects plots for circular test article.

For the circular test articles, a Kolmogorov-Smirnov test was applied to the percentage dimensional error data. The eight treatment groups were each subjected to the Kolmogorov-Smirnov test at the 5% significance level. The test validated the hypothesis of a normal distribution across all treatment groups. Figure 16 contains a plots of the empirical cumulative distribution function obtained from the $N = 128$ data points, using the overall mean and standard deviation of the samples to normalize and provide a visual comparison to the standard normal curve.

Figure 16. Plot of the overall empirical cumulative distribution function (CDF) of z-values for all circular test article percentage deviation sample data (all treatment groups combined) from the square test article versus a standard normal CDF for visual comparison of normality.
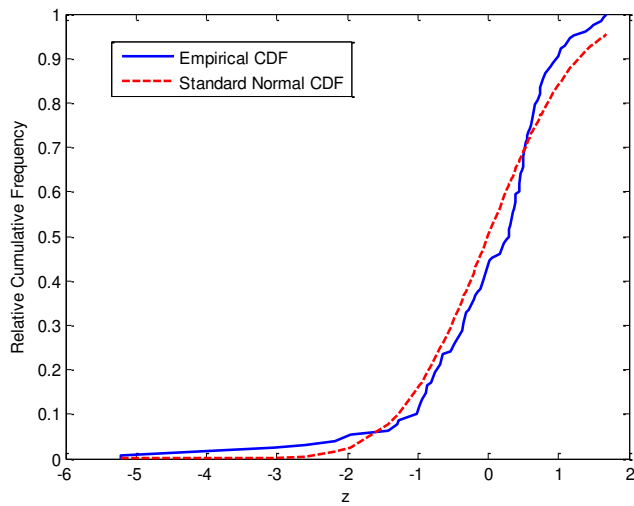
The ANOVA analysis (results in Table 4) revealed that only one of the main or interaction effects observed was statistically significant. The p-value for the size factor, showed an approximately 0.9% probability that the observed differences between treatment groups were due to random chance, well below the chosen 5% significance level.

Table 4

Three-Way Analysis of Variance of Factors Affecting Dimensional Percentage Deviation in Circular Test Articles

Source	*df*	SS	MS	*F*	*p*
speed	1	0.00029	0.00029	3.59	0.061
size	1	0.00056	0.00056	6.97	0.009
shell	1	0.00008	0.00008	0.96	0.330
speed * size	1	0.00016	0.00016	2.04	0.156
speed * shell	1	0.00001	0.00001	0.13	0.719
size * shell	1	0.00003	0.00003	0.41	0.524
Error	121	0.00968	0.00008		
Total	127	0.01081			

Because multiple types of data were collected for each test article, it was deemed potentially instructive to chart the data, categorized by type, considering the differently sized test articles, the different axes from which the dimensional data was obtained, and whether the dimension was from an inner, outer, gap, or thickness location, as defined in Figures 6, 7, 8, and 9. The summary chart of averages is shown in Figure 17.
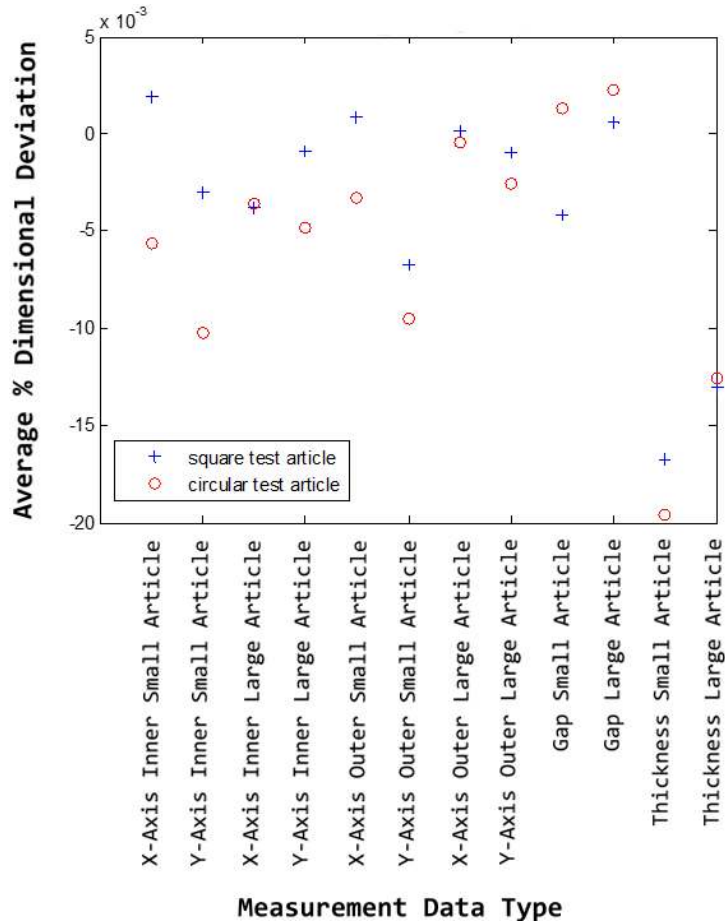
Figure 17. Mean percentage deviation for specific categories of dimension types.

It is apparent from the average percentage dimensional deviation data that the thickness-type data exhibits a greater error than other dimensions. A relatively small sample set can be expected to result in studies with low power, where it may be possible to erroneously fail to detect a statistically significant difference. Although an ANOVA analysis is unreliable with

small numbers of data points in each treatment group – in this case only four data points per group – it was deemed potentially instructive to perform a design of experiments ANOVA analysis on the square articles' thickness data, alone, in order to search for patterns that might lead to future studies performed with greater samples obtained for these specific, targeted data types. The results appear in Table 5.

Table 5

Three-Way Analysis of Variance of Factors Affecting Percentage Deviation in the "Thickness" Dimension of Square Test Articles

Source	*df*	SS	MS	*F*	*p*
speed	1	0.00004	0.00004	0.94	0.341
size	1	0.00009	0.00009	2.28	0.144
shell	1	0.00000	0.00000	0.00	0.958
speed * size	1	0.00001	0.00001	0.16	0.688
speed * shell	1	0.00006	0.00006	1.68	0.206
size * shell	1	0.00001	0.00001	0.16	0.688
Error	25	0.00095	0.00004		
Total	31	0.00115			

For the most significant interaction effect – print speed interacting with shell thickness – the confidence interval was calculated and the plot appears in Figure 18.

Discussion

The mean of results for all factors with the square test articles were centered around a dimensional deviation of approximately -0.387%, a value which is comparable to many typical techniques for manufacturing mechanical components. By way of example, using subtractive manufacturing techniques such as milling and drilling to achieve a hole similar in size to the 32.5 mm inner dimension of the test articles used in this study, Sandvik AB (2011) lists the achievable precision grade as IT9/10, with 33 mm as the outer limit for these particular grades. IT10 would corresponds with a dimensional tolerance of +/- .219% (Coban Engineering, 2015).
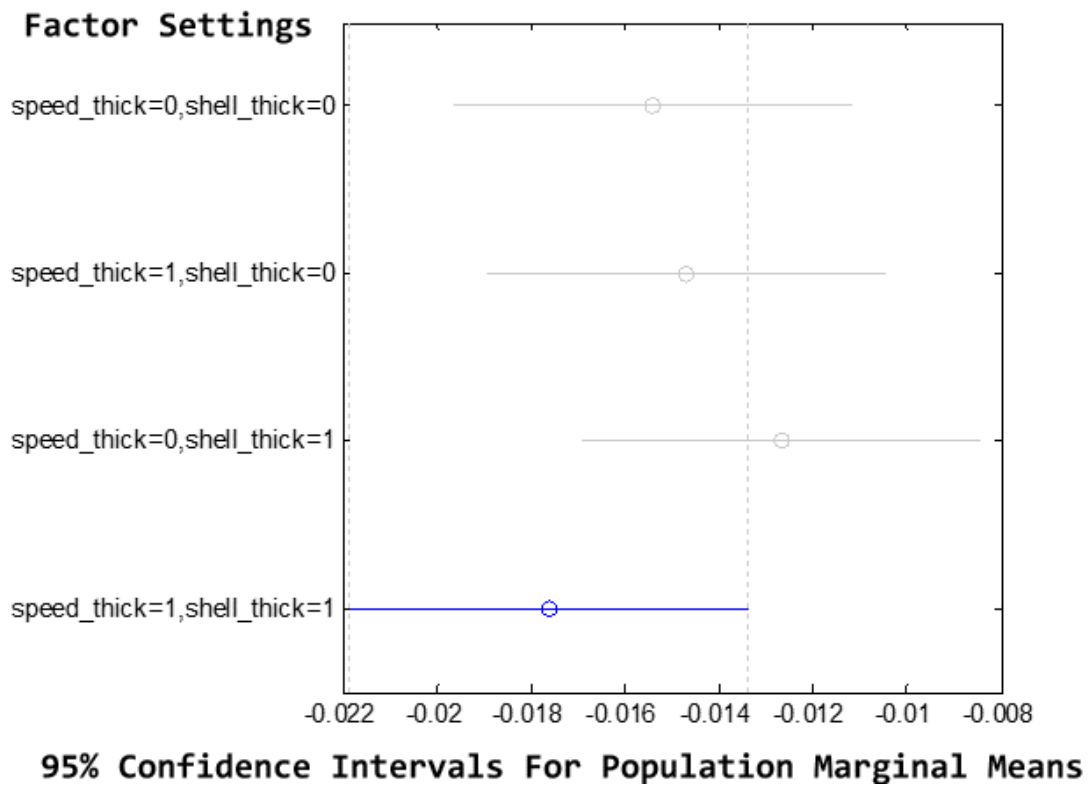
Figure 18. 95% confidence interval plots for square test article thickness data, demonstrating a statistically insignificant but notable difference when printing at high speed with thickest shell settings. Circles represent estimated population marginal mean values. Abscissa numeric values represent fractional dimensional deviation.

From the standpoint of creating components with repeatability and precision, addressing the several factors described in the method section of this study – low tessellation precision, improper slicer settings, bottom layer inaccuracy, extrusion/flow miscalibration, exceeding printer extrusion rate capabilities, improper bed leveling, print warpage due to poor adhesion, selection of dimensions which are not multiples of the print nozzle width or the selected layer height, infill settings which result in excessive jerk at edges of the print, and retraction errors due to re-priming the nozzle – appears to have removed a significant fraction of observed print dimensional

imprecision. None of the test article measurements exhibited an average error exceeding one percent, except the thickness-type dimensions.

The DOE analysis for the square test article reveals some interesting trends with respect to main effects (Figure 11). Thicker outer shells, smaller sizes, and slower speed all appear to decrease dimensional precision. The differences are not, however, dramatic and, indeed, were shown by the subsequent ANOVA analysis (Table 3) to be statistically insignificant. The observed trends are still instructive, however, particularly when looking at the interaction effects shown in Figure 12. Increasing speed to increase precision might appear counterintuitive, but the interaction plots between speed and shell thickness and between size and speed, respectively, reveal that the increased print speed provides greater precision when printing with thicker outer shells or smaller objects. When the test article wall thickness was narrow or the object was relatively large, greater precision was achieved with a slower print speed. It would appear that with greater material deposited in close proximity – either to build up a shell or because the object is physically small – the lingering of the print head may cause melting or expansion of previously deposited material. It may also be possible that an inability to reliably repeat positioning upon subsequent passes results in print imprecision, whereas a quicker traversal somehow minimizes the effect. This is a consideration for a future study.

In addition, because a print head passing through an arc naturally deposits greater material at the inside of the arc versus the outside, there is an inherent inaccuracy that comes with printing arcs as opposed to straight lines. This inaccuracy becomes more pronounced with smaller objects, as the excess material deposited represents a greater fraction of the object dimension. Slicer software manufacturers and individual users have attempted to introduce arc compensation (Alexrj, 2013) without success. Other sources cite material properties as being the source of error

in hole dimensions. Hodgson (n.d.) writes, "Plastic shrinks when cooling. Different kinds of plastic exhibit different shrinkage, which might also depend on temperature. Because of such shrinkage, circular (or polygonal) holes laid by the extruder at the nominal diameter will end up smaller after cooling" (para. 4). For these reasons, the ANOVA analysis results demonstrating a statistically significant factor in size for the circular test articles can be interpreted not as an inherent inability to print small circles or arcs but as a type of printing for which trial and error are required in order to compensate, until a more encompassing model is developed. Again, this is an area for future study.

Figure 17 shows that the greatest differences between circular and square test articles occurs for smaller test articles. Beyond those differences, the two types of shapes do not demonstrate an appreciable difference other than what can be expected due to random variation. Because of the relatively precise values of dimensional deviation revealed in the study, small contributors of inaccuracy may be considered to factor into the quantities observed. Measurement error is a contributor worthy of note. In particular it was appreciably more difficult to measure the small circular test article versus the small square. It was difficult, due to the nature of the test article size and the adjacent gap/thickness component, to obtain consistent positional contact with the small circular test article. As the items are plastic, and hence pliable, the reduced surface area for the small circles to contact the caliper also translates into the pressure applied by the caliper possibly flexing the smaller articles. This may well be a significant contributor to the appreciably poorer average dimensional deviation exhibited in Figure 17 for small circular articles. Indeed, in looking at the interaction effects, it appears that the smaller and thinner circular test articles (Figure 15) deviate quantitatively and trend-wise from their square counterparts (Figure 12), but the larger, thicker articles do not.

As explained in a National Physical Laboratory guide on good measurement practices (Flack, 2014),

> The use of polymer materials for machine parts is extensive and they require accurate dimensional measurement. These materials are often soft and the measuring force applied by ordinary callipers and micrometers can deform them, resulting in inaccurate measurements. Consequently, this has led to the development of constant force dial calipers…that allow the measurement of materials that are easily deformed. (pp. 20-21)

Though such constant force calipers were not available for this study, Flack (2014) goes on to explain that there is an additional source of measurement error when using calipers with circular test articles:

> Inside diameter measurements made with M-type vernier calliper involve measurement errors that are inherent to the design of the jaws. These errors are more significant when measuring small holes and result from the measuring face of the jaws being offset from the centre line of the hole. It is therefore necessary to take these errors into consideration and make necessary compensations or use another type of instrument if greater accuracy is required. (pp. 22)

Future study planning should take into consideration the use of different types of instruments in order to achieve consistent measurement reliability across test articles – from drill gauges to 3D scanning.

As the overall dimensional precision of the test articles was better than anticipated, and the observations of interest represented less than one-half of one percent dimensional variation, it was appropriate to consider additional factors and reevaluate the potential causes of variation with much greater resolution appropriate to this new context, to pave the way for future studies.

Focusing on the largest errors in Figure 17, thickness-type dimensions seemed to pose a particular difficulty for the printer. The ANOVA analysis of the square test article thickness data points – keeping in mind that there were only four samples per treatment group – seems to indicate that the factors I have considered in this study are not a significant contributor to that particular type of error and the greater than 1% bias noted. The best indicator of some discernible performance difference is shown in the confidence intervals of Figure 18, where a thick shell and high speed printing do provide an appreciable, if statistically insignificant, decrease in dimensional accuracy.

Considering other possible sources of this imprecision, the following should be noted: The printer's ability to maintain the maximal requested extrusion rate – the volume of material we expect the printer to be able to deposit in a given time – is a more complex consideration at these small dimensional deviation values. Rather than simply focusing on a threshold value for maximum extrusion rate, defined by the test demonstrated in Figure 4, the extrusion rate varying with different features – jerk and temperature variation within the hot-end control loop, for instance – may influence results. Rather than relying on the printer settings for material thickness in order to set the nominal extrusion rate, it is recommended that empirical measurement of the extrusion rate be performed to calibrate all contributions to extrusion in order to remove any bias.

From the Cura slicer software manual (Ultimaker B.V., 2015b):

Infill Speed [6]: The speed at which infill lines are printed. If set to zero then same speed is used as for the rest of the print. A slight loss in outer quality can be expected if you use this to print a fast infill due to changes in nozzle pressure when switching between outside and infill parts.

Minimal layer time [7]: The minimal time spend on printing a single layer. If a layer

takes less time to print then this configured time, then the layer is slowed down. This

ensures that a layer is cooled down and solid enough before the next one is put on top.

These somewhat ambiguous statements about nozzle pressure differences and the requirements of

allowing layers to cool down certainly can be taken to imply that other variables not included in

this study and not discussed in the public literature, to date, may be sources of dimensional

variation. The slicer software includes settings for cooling fan speed, and the toolpath, itself,

affects how long the hot print head lingers over a particular area of the print, which, in turn, may
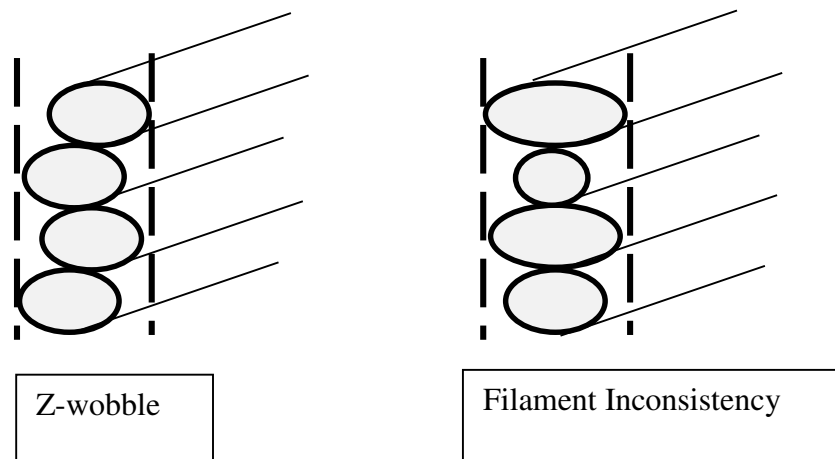
affect deformation.

Figure 19. Illustration of z-wobble effect and filament inconsistency effect, respectively, on measured dimension of fused deposition layered objects.

When all other contributions to dimensional imprecision which can be mitigated have been

accounted for, there remain certain inherent sources of error due to the design of fused deposition

modeling machinery. Linear motion of a print head moving in the x-y direction, followed by

subsequent, dependent layers added in the z-direction is subject to errors in repeatability, where

the print head simply cannot line up perfectly where the user intends with each subsequent layer

(Figure 19). This inherent variation has been categorized by related terminology – z-wobble and

backlash – and the error may be contributed to by either the linear motion of the print head or the characteristics of the raw filament material itself ("Taxonomy of Z axis", n.d.).

As explained by Hodgson (n.d.), "Backlash is a mechanical defect of one or more axes that basically reduces the amount of actual motion whenever a motor inverts its spinning direction" (para. 11). Any loose connection between the driving motors and the print head – often caused by incorrect drive belt tension – can contribute to backlash. Because the x-y motion of the print head is not precisely what was requested, due to backlash, z-wobble can be expected to occur. As with many other types of linear motion, it can be expected that the greater the amount of motion in a particular layer – a function of the intricacy of the part or parts being printed and the slicer software's elected toolpath – the more pronounced the random variation that will be observed in the z-wobble effect.

Similarly, filament diameter is assumed to be uniform throughout an entire roll of raw material. Adjustments for this filament size are typically fixed settings in the printer. If the filament exhibits inconsistency across its length, however, this will change the rate of material extrusion throughout the print duration, resulting in dimensional imprecision. Both print head linearity effects and filament inconsistency are left for a future study to investigate.

Conclusion

The results of this study have shown that dimensional precision is affected by a variety of factors, many of which are within the control of the user. While insight was provided into certain trends in printer performance, it should be noted that the dimensional variation of the test articles created for this study was so small that the printer precision was comparable to other modern-day manufacturing techniques. The small biases observed appeared to be consistent. For this reason, the printing errors I removed from affecting the prints, as outlined in the method section, are of

great practical importance. In practice, trial and error could be applied to discover the nature of the relatively consistent biases in order to remove them from future prints. Anecdotal evidence suggests that measurement error in this study is likely as prominent a component of variation as dimensional differences, in the small range of values observed. Other factors, such as arc compensation, filament inconsistency, printing multiple components simultaneously – both temperature/proximity effects and repeatability of complex linear motion such as z-wobble and backlash - are left to a future study.

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