Measurement Systems Comparison on Various Feature Sizes of FDM Parts.

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ABSTRACT

12 identical FDM parts were produced in ABSM30, each having 16 features for replicated measurements. Half the features were positive (posts), half were negative (holes). Half of all features were rectangular, half were round. Two different CMMs with 1.5mm touch probes were compared, one CMM additionally used a laser, and manual measurements were taken with gauges and calipers. All features were measured using these 4 measurement systems. All measurements were compared against the theoretical feature size to generate a percent error value. The laser values were notably different than both probe values. The manual measurements were similar to one of the two CMM probes. Positive versus negative features were significantly different in 7 of 8 cases. Feature size and measurement error were inversely proportional. The largest features had the least amount of error in all cases while the features below 6mm had the most error and high variation.

Keywords— CMM; gauge blocks; gauge pins; calipers; FDM, 3D printing, 3D scanning, error compensation, sources of variation.

INTRODUCTION

3D printing requires first having a 3D solid The technology of Additive Manufacturing (AM) is experiencing rapid growth, and its applications continue to expand. Many applications require greater accuracy of fabricated parts, as well as accurate measurement of the parts. This is the case for Fused Deposition Modeling (FDM), a type of AM process, originally developed for rapid prototyping. Applications include customized tooling and medical devices. Improvements in raw material strength will increase the application for small lot or single piece manufacturing of tooling and lightweight parts. Bioengineering applications have been developed, such as biodegradable scaffolding for tissue grafting, drug delivery systems, and anatomical models for planning surgical procedures.[1,2] An example is use of polymethylmethacrylate (PMMA), which is available in a medical grade, is FDA approved, and is suitable for use in FDM. The adaptation of FDM to produce items with medical applications using PMMA, such as in reconstructive surgery, has been investigated.[3] Many medical devices have plastic housings or components that require features and sizes to be very accurate. For applications of this kind, precision and accuracy of the part become critical.

3D printing first requires having a model of the part to be manufactured. This can be created in solid modeling software, or produced from a process called reverse engineering. This is done by sending the output from a 3D scanner to special software that converts the 3D scanner output into a solid model. That conversion process in software is not yet robust and mistake free.

Resulting solid models are often low quality with negative internal pits or unintended positive external features that carry through to the 3D printer. There have been many recent advances in reverse engineering, in both hardware and software.

In biomedical applications, the CAD file may be created from computed tomography (CT) scans.[2] While accuracy is critical for this type of application, the process also requires a balance between the subject's exposure to radiation and the level of detail needed for accurate reproduction.

There is great interest in improving reverse engineering along with expanding the possibilities of 3D printing. The long term goal is to be able to place an object before a 3D scanner and then 3D print a 3D copy at the touch of a button. The current state of the technology is far from that pipe dream but seems to certainly make progress each year. This work attempts to contribute to that effort through characterization of measurement systems and error.

During the process of conversion of a CAD file, first to an STL file, and then to a three-dimensional object, there are multiple sources of error. Error sources in the FDM process fall into two general categories, those resulting from the file conversion process, and those resulting from machine process parameters.

Errors that can be related to the CAD to STL file conversion process can be caused by the slicing and triangulation performed by the software. Since these result in approximations of the form, loss of fine structure may result. This can be improved by decreasing the width used in the slicing step.[1] The same change can reduce the stair-stepping effect, which results from the layers deposited in step-wise increments. If the process includes conversion from a file created by 3D scanning of the object, or CT imaging of a patient[4], additional error can result during the software conversion to an STL file.Similar errors result from machine process parameters. A larger extrusion nozzle diameter can result in loss of fine structure. Along with the layer height, the nozzle diameter also contributes to the stair-stepping effect, which contributes to surface irregularities.[4] There is a tradeoff in FDM, with smaller extrusion diameter and layers improving resolution of fine structure, but increasing the machine time. If the rate at which the filament is deposited is not aligned perfectly with the rate that the extrusion head moves back and forth and turns, there will be errors resulting from slightly too much or too little material deposited at points in the process. Temperature of the melting chamber and the box is a factor here too; the plastic filament solidifies as it is deposited, but takes a finite time, during which distortion can occur. Other factors impacting finished geometry include material shrinkage rates, glass transition temperature, moisture content, thermal history, gradients, machine vibration, tool path algorithms, solid model quality, and support material quality; in addition to variations within the extrusion process itself and the table motion.

During product development, dimensions are often modified ever so slightly for improvements to fit and function. FDM is ideal for prototypes and development work. It was invented for this purpose and is still commonly used in this way. It would be used even more for this and likely used for production parts if the precision level was improved, which is the intent of this research.

FDM printed parts are built with locally specified porosity, having different densities in various regions within each part. They also have different surface roughness on the bottom, sides, and top of each part. The quality and precision of each feature is dependent on the location and orientation of the feature. A feature printed in one direction could be geometrically different than the exact same feature printed in a perpendicular direction.

Compared to some of the traditional manufacturing processes for plastics such as injection molding, extrusion, machining, blow molding and others, there seems to be more variation in the feature dimensions of FDM printed parts.

This research quantifies some of that variation If the main sources of variation can be identified and predicted accurately, then software could easily compensate for error prior to “printing” the part.

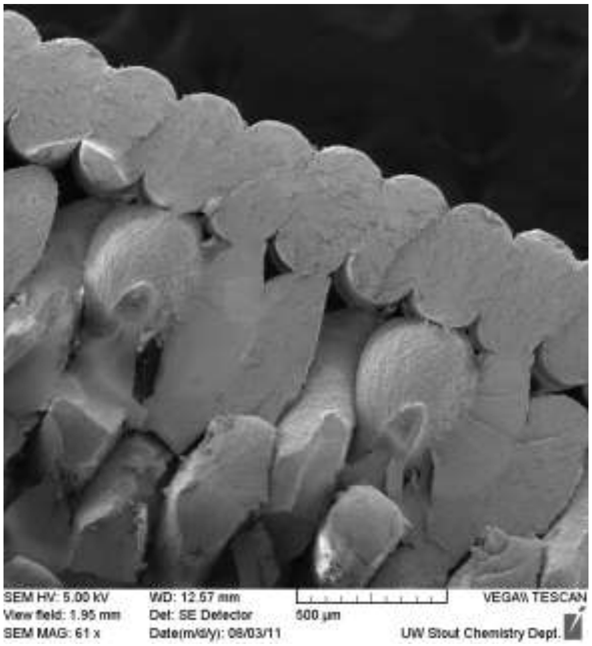


Figure 1. Micro-scalloped surface visible in an SEM image of an FDM tensile specimen at the point of fracture, in cross section view.

FDM printed parts are porous and surfaces have a micro-scalloped surface texture due to the nature of layer deposition (Fig. 1). As expected, the resulting parts have macroscopically inconsistent features which are influenced by many different process and machine parameters.

Orientation of an object in 3-dimensional space during fabrication is also a variable affecting accuracy of FDM parts. The thread of molten thermoplastic extruded in 3D printing can be laid in various build orientations, patterns, and densities; all of which influence mechanical properties. Many researchers have quantified the variations in mechanical properties due to various build orientations; some have also quantified accuracy of the geometry relative to the orientation. The XY table itself has good repeatability, but the vertical direction (Z) perpendicular to the XY table, has precision defined by many other parameters and is calibrated differently and separately than the table. This results in anisotropic dimensional error and is measured in this research

This research quantifies the variations in physical feature size resulting from two different build orientations. 12 parts were built from two STL files whose only difference was text labels. Each part had 16 separate features to be measured, half positive geometry (post) and half negative geometry (holes). All feature sizes were identical in the STL files so they were theoretically identical for all 12 parts. Each measurement was taken by four different measurement systems for comparison. One file was vertically oriented as 3D printed and the other was horizontally oriented as it was 3D printed making six of each type.

The intent was to produce known error in one direction on half the parts and a different error, perpendicular to the first, on the other half of the parts. Additionally, the experiment was replicated on two different FDM machines, a Vantage and one from Fortus 3D Production Systems. There were easily visible differences in the parts from these two machines and are explained in this paper.

Physical dimension measurements can be as simple as a tape measure and as complex as a lidar system. Several options are available along this continuum of possibilities. In manufacturing, the common measurement instruments are the 150 year old classics; height gauges, surface plates, gauge blocks, gauge pins, micrometers, and calipers. These are commonly available and quality versions can be purchased for less than $100. For high precision, a coordinate measurement machine (CMM) is the most common instrument which cost about the same amount as a new car.

Machine vision is another measurement option and this technology is changing rapidly with 3D vision increasingly used as the prices continue to drop. Structured light scanning is yet another technology used in manufacturing to measure shapes and sizes. Each one of these measurement technologies has different costs, advantages, and dis-advantages.

The nature of the fabrication process results in irregular surfaces, which provide a challenge for measurement systems. In this research, manual measurements and CMM, are compared. Manual measurements with gauge blocks, gauge pins, calipers, and micrometers are considered to be the least accurate and are certainly the least expensive. CMM measurements are considered to be the most accurate and are certainly the most precise.

Notably, the CMM is a contact type of measurement with a ruby tip mounted on a very precise spring loaded post. Motion of the post is detected electrically once the ruby tip makes contact with a surface. The radius of the ruby tip is then used to calculate the actual location of the surface. Features on a part are always measured using numerous points of contact on a surface. A flat surface for example is considered to be a perfect plane, the ruby tip is touched against the surface in 30 to 50 locations and linear regression is used on the data to calculate a theoretical plane location and angle.

However, in FDM printed parts there are many discontinuities along surfaces and features. If the ruby tip touches a discontinuous area or problem, data is collected that does not lie along the true surface. This is especially of concern along the micro-scalloped surfaces of a 3D printed part. The ruby tip touching the top of a micro-scallop versus the valley in between two micro-scallops, will introduce measurement error. This research explores this type of error. Figure 2 demonstrates differences due to the micro-scalloping.

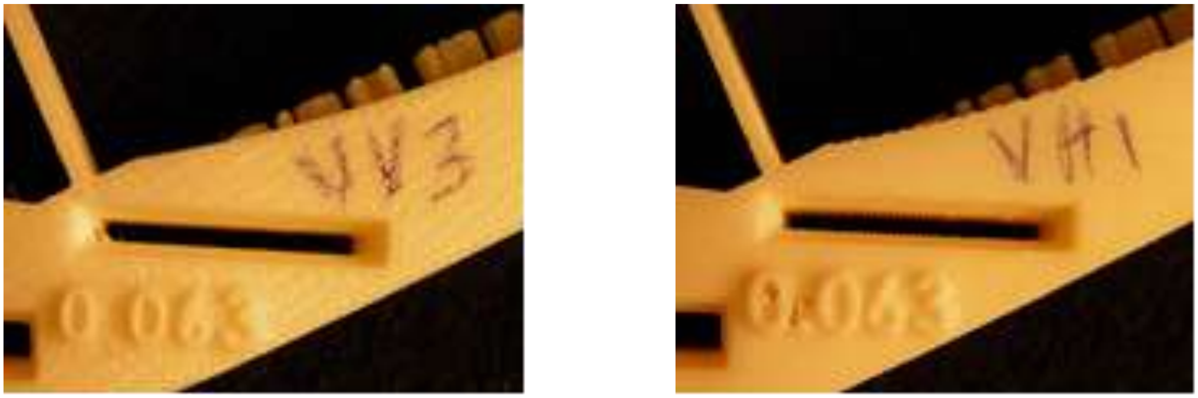


Figure 2. Photo record: Left is 1.6 mm slot printed vertically. Right is 1.6 mm slot printed horizontally; displaying more micro-scalloping in the horizontally printed slot.

Similarly, each layer of a 3D printed part must have a start-finish point of the extruded plastic bead. If the software selects those to be vertically stacked on top of each other, it is called a seam. Sometimes the seam is advantageous and sometimes it is a disadvantage. Good 3D printing software has options to specify these features of the seam.

When programming CMM measurements, the seam can easily be avoided. This is not true of manual measurements. A hole for example, in a FDM printed part will have a seam on the inside diameter. Inserting a gauge pin into the hole will be restricted by the seam such that a smaller gauge pin is required. This introduces measurement error. In this case, the CMM will produce a more precise overall inside diameter, and yet that data ignores the presence of the seam. Measurement error due to the presence or absence of a vertical seam did not exist prior to 3D printing. Similarly, with the micro-scalloped surface from 3D printing, measurement error of a new type must be considered. That concept is explored in this research.

Lastly, the cost of measurement should be considered along with its level of precision as an important aspect of the adaptation and acceptance of 3D printing. If the precision of low cost manual measurements is shown to be close to the level of precision found in a CMM, then many more users could easily measure their own 3D printed parts.

This would expand the use of 3D printing for manufacturing since the need for precision and verifying accuracy is so important. This is the significance of the contribution of this research to the general public. Similarly, if 3D scanning can be compared to low cost manual measurements, users could easily compensate for scanner error.

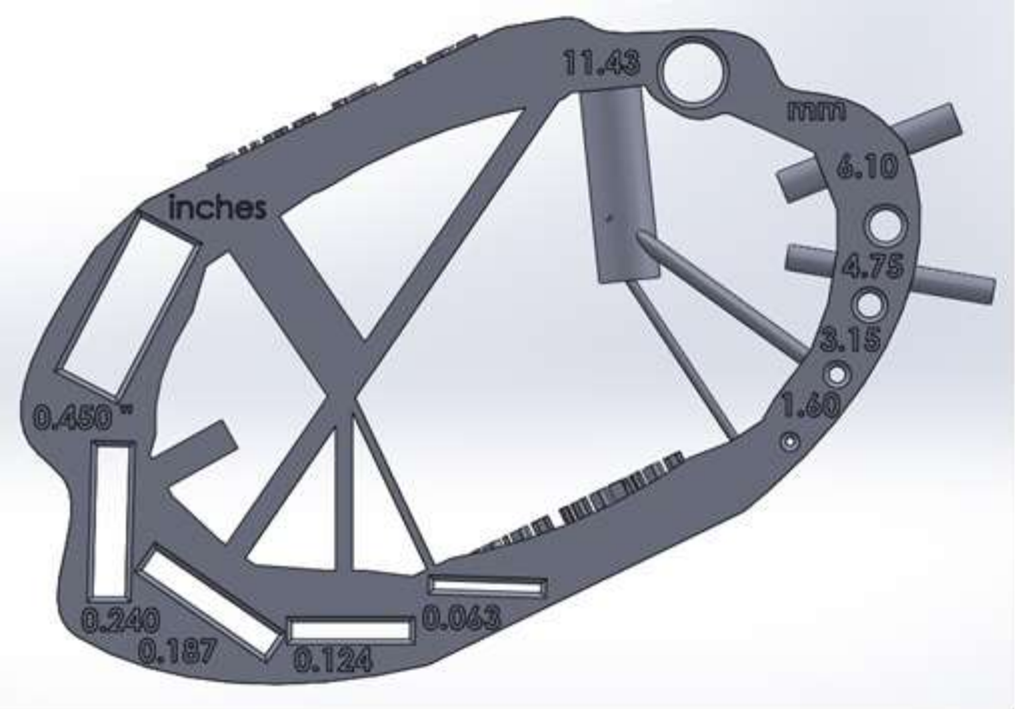


Figure 3. The standard part designed and used in this research.

The ASTM F42 Technical Committee on Additive Manufacturing is working to develop a benchmarking test piece, which could serve as a standard. A measurement system for the assessment of the geometric performance of an AM system is also underway. Development is not complete, however.

This paper introduces the idea of a standard 3D model published free to any user, which could be 3D printed on any machine and then easily measured using gauge blocks, gauge pins, and calipers. This would give the end user of 3D printing technology the ability to easily compare actual feature sizes to the theoretical model dimensions using only measurement instruments already in their facility.

At very little to no cost, without wait time, users could then fine tune their 3D printers to compensate for inherent error in either the 3D printing or the 3D scanning, or both. It will also allow end users a low cost method of comparing precision from different machines and/or different software settings. This will advance both of these technologies by improving precision in existing facilities at essentially no cost to anyone.

This first generation standard part was created for this research. It is shown in Figure 3. Notice the feature sizes were selected so that nominal values are easily displayed in both SI and English units. This is to make it more versatile so that it is easy for all companies to measure, regardless of whether their set of gauge blocks and gauge pins are SI or English. The authors recommend against this in the second generation standard part. Rather, it is best to develop two standard parts, one for SI units and the other for English units. That is the topic of future research.

Half of the parts in this research were 3D printed vertically while the other half were 3D printed horizontally. Those two words were printed directly onto each part for identification. Those words on each part are not visible in Figure 3.

EXPERIMENTAL

This work was performed using two different FDM machines, a Vantage-XA and a Fortus400mc printer. Three replicates were made on each machine in each of the two orientations, and the same STL file was used for each set of parts.

Measurements were performed using 4 measurement systems, summarized below:

Equipment used for collection of measurement data

Data set	Equipment	Probe	Source
1	CMM Brown & Sharpe Global□ Advantage	TP 20 probe with1.5 mm tip	Bowman Tool and Machining, Inc. Rochester MN
2	CMM Optical Gaging Product (OPG) SmartScope® Flash™ 250	1.5 mm ruby touch probe	University of Texas - Austin
3	CMM Optical Gaging Product (OPG) SmartScope® Flash™ 250	laser	University of Texas - Austin
4	Manual measurement equipment	Not applicable	University of Wisconsin -

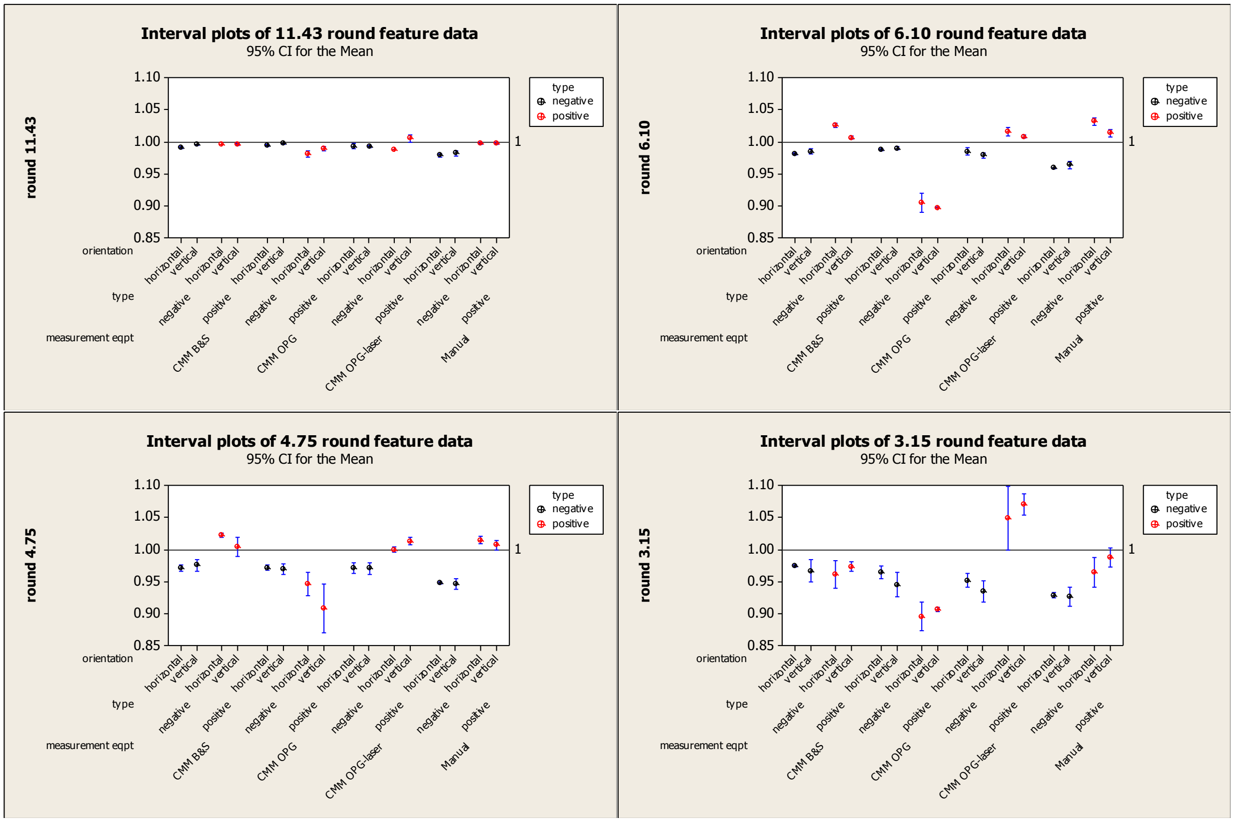
caliper, gauge pins and blocks,	Stout

Each of the four sets of measurements was performed by taking three measurements on each feature of each part. The measurements for each feature were compared with the planned value for that feature, and expressed as a ratio. This allows direct comparison of the measurements for the various sized and shaped positive and negative features.

RESULTS AND DISCUSSION

ANOVA was performed for each of the four feature sizes of rectangular geometries and four feature sizes of round geometries. The factors of printing machine, build orientation, geometry (positive vs. negative), and measurement equipment were used. Nearly all factors were found to be significant in the eight ANOVA's, making it difficult to draw conclusions. There was no apparent pattern to the factors that were found to be insignificant: At 90% confidence 3 of the 8 showed orientation and 3 showed printing machine to be insignificant factors, but with no trend.

Interval plots representing this data are shown below. They have been normalized so that each graph represents the same scale, to enable visual comparison of the measurement range.



Interval plots of 11.43 round feature data

95% CI for the Mean

Interval plots of 6.10 round feature data

95% CI for the Mean

Interval plots of 4.75 round feature data

95% CI for the Mean

Interval plots of 3.15 round feature data

95% CI for the Mean

Figure 4. Round features, Y-scale normalized

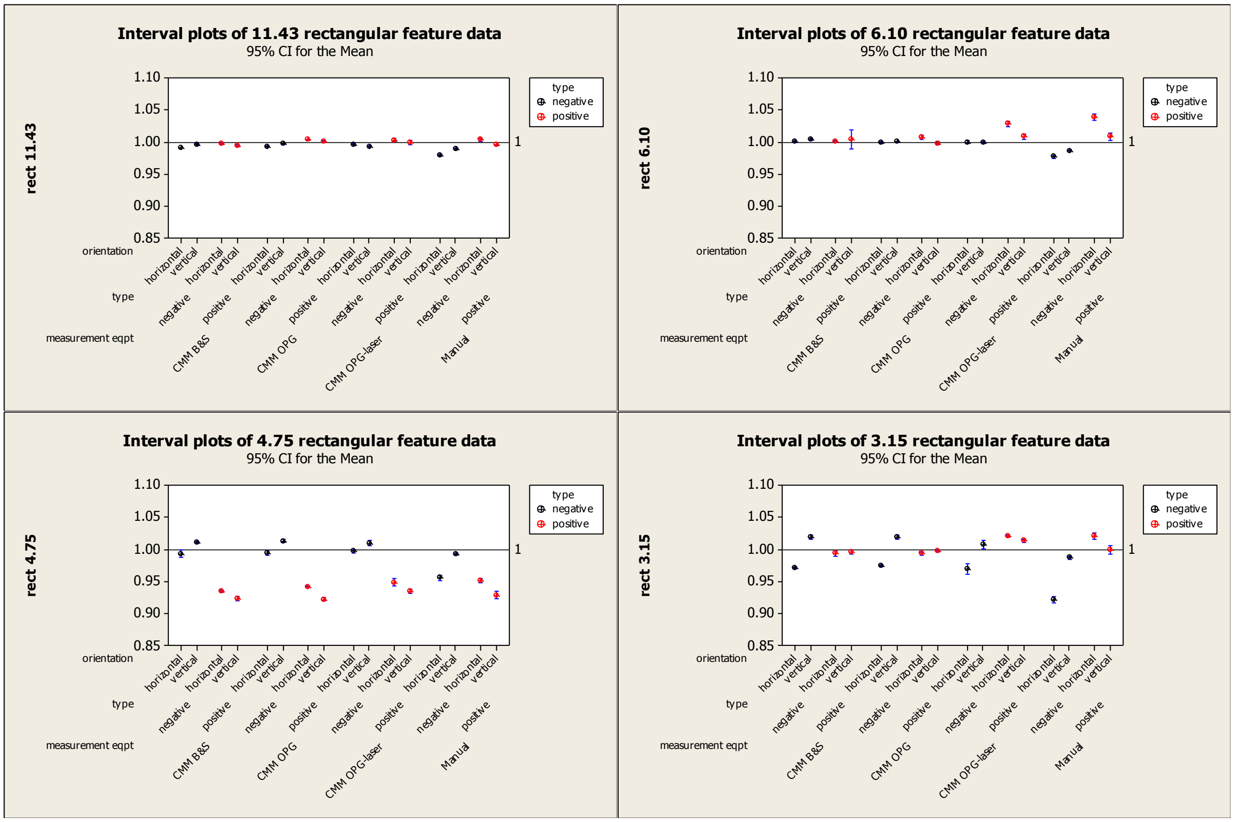


Figure 5. Rectangular features, Y-scale normalized

Three general trends are easily visible from the interval plots. Feature size variations are definitely worse for the smaller feature sizes. Clearly the variation in the measurement data is greater for the round features compared to the rectangular features. This seems to be related to variation in surface finish of the round versus rectangular features. A third trend is that the measurements on average overall are lower than the planned or theoretical size. The exception is the 6.10 mm rectangular data. It is not clear whether this is due to shrinkage, error in the data file, or some other factor.

In order to make more meaningful comparisons, we decided to evaluate more intently the data of the 11.43mm features. Our reasoning was that if we know both actual feature size error and variation are greater on the smaller features, then extracting only the data of the largest feature size (11.43mm) would yield the most meaningful comparisons of measurement systems, feature shape, and build orientation.

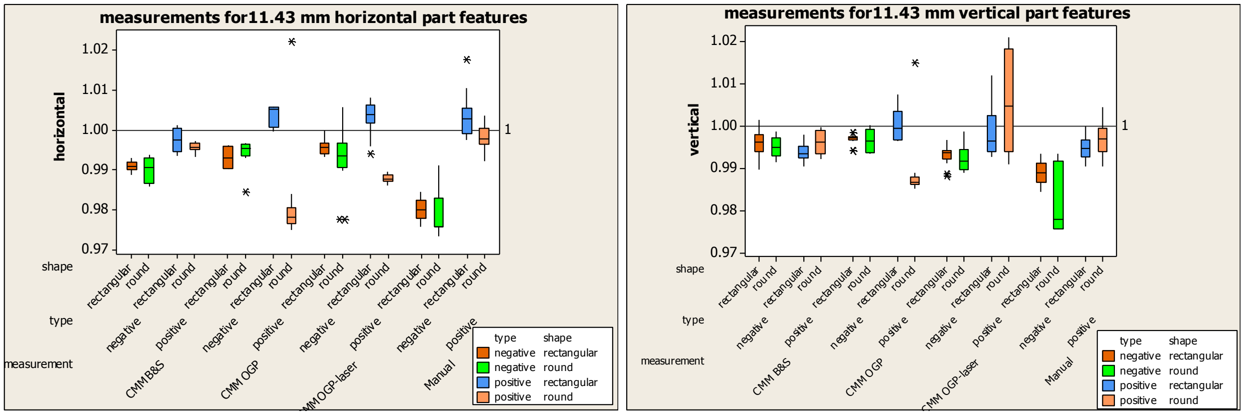


Figure 6. Boxplot of measurements of 11.43 mm features

From the 11.43 mm box plots, we observe a noticeably wider variation in the data for the laser measured positive features within the vertical build orientation. We know the vertical build orientation produces a lower quality surface finish, so we expect that could be creating variation in the laser measurement.

From the 11.43mm box plots, we observe the manual measurements from the negative feature sizes tend to have nearly a 2% error whereas the manual measurements for the positive feature sizes tends to correlate well with the CMM probe measurements. This is good news for low cost measurements in production settings. It means that for positive geometries of FDM parts, 12mm and larger (those usually measured with calipers) the inexpensive caliper measurement is very accurate.

SUMMARY AND CONCLUSION

Variations in measurement can be influenced by multiple factors such as true size error, surface finish, expansion or contraction, CMM measurement software methods, build orientation of the parts, and many others. For example, visual inspection reveal a trend in the data of the 4.75mm rectangular feature data; but for this size only and only for rectangular features. In this data, the positive features have approximately 5% error whereas the negative features have very little error. Further experimentation would be required to ascertain possible reasons for this trend.

Finally, the 11.43mm box plots indicate that both of these simple low cost measurement systems (calipers and gauges) when used on FDM parts will likely be within +/- 3% of the true measurement as measured by a CMM probe or a laser.

The most significant finding of this research is the correlation of the manual measurements with the CMM probe measurements. However, measurement of internal features of FDM parts that are 12mm and larger with simple gauge blocks and gauge pins is not nearly as accurate as calipers on positive features.

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