A Systematic Use of Reverse Engineering in Evaluating the Overall Accuracy of the Fabricated Parts

Abel Ardis, Andres Alvarez Andrade, Justin McNamara, Anthony Ahrens, Jason Janysek, Jamie Humble, Bahram Asiabanpour[1]

Ingram School of Engineering- Texas State University- San Marcos

In this paper a systematic approach is proposed that evaluates the overall accuracy of a part. In this approach, by using the feature taxonomy, a part is decomposed into primitive features. Then, each feature is compared to the original CAD. Features are evaluated based on their size, form, orientation, and position. Laser scanning technique is used to collect a feature's data and its conversion into CAD data. To reduce data processing time for non-freeform features, manual digital dial indicators were customized and used for data collection. To process and evaluate the part's accuracy, statistical and CAD methods are applied. One benefit of the proposed hybrid system is that different errors can be differentiated and separated. In this study the manual method and statistical line fitting showed that, in addition to the surface quality deviation error, there was a trend error in the data; as the part got closer to the front right side of the printer it was steadily increasing. Further observations clarified that the trend error is caused by the build orientation; as the printer lays down a new layer of powder it drags the previous layer binder and powder from the back of the printer to the front of the printer.

1. Introduction

Based on measurement and data acquisition techniques, reverse engineering allows to gather all the information needed to reproduce, fix, and/or improve a specific part. The quality and the accuracy of the data collected directly affects the final outcome. Calibration, accuracy, fixturing, and the surface finish are some of the major problems that one could find during the data acquisition process (Várady, T., Martin, R., & Cox, J., 1997). Consequently, different

[1] Email: ba13@txstate.edu

technologies have been developed to optimize the data acquisition process to generate a CAD/CAM file and minimize the impact of measurement errors. To ensure that the data acquired is usable, a careful analysis is normally performed before selecting a method. Nonetheless, a standard method to calculate the error between the original piece and its replication has not been defined. An error analysis must be performed in order to determine whether or not the measured model corresponds to the original CAD. Different approaches could be performed in the error analysis. Weber, T., Motavalli, S., Fallahi, B., & Cheraghi, S.H. (2002), Yau H. T. (1997), and Narayanan Namboothiri V. N., Shunmugam, M. S., (1998) describe different data accuracy and error analysis methods, such as, linear approximation techniques, least-square method, and geometric and surface shape evaluation. Cheng, J.T., Zhao, W. L., Xie, X. D., (2009) made an improvement of the method of data quality assessment, while Wu, X. M. does an error analysis and precision evaluation of reconstructed surfaces in which the accuracy of a CMM machine is evaluated (Wu, X. M., Yu, G. B., Li, G. X., Shan, D. B., 2011). The above computerized/automated system resolves the limitations of the manual systems including time consuming and human error. However, the automated system are accompanied with the limitation that the model's geometrical data is measured as bulk and does not make any distinction between different sorts of errors. For example, they don't differentiate between the error initiated from dimensional accuracy, geometrical form, and surface quality. To address this problem a hybrid system is proposed that, by using both manual and automated (laser scanning) systems, evaluates the overall accuracy of a part based on the feature taxonomy.

The rest of the paper is organized as the following. In section 2, methodology of the research including the taxonomy of the parts, the details of the manual and laser scanning-based method are explained. In section 3 the method is explained through a case study. Section 4 illustrates the results of the case study. Finally, conclusions and discussions are presented in section 5.

2. Materials & Methodology

A hybrid method is used to calculate a parts accuracy in which manual and computer based methods are combined (Figure 1). Starting from a physical model, two different methods are performed in order to calculate the part accuracy. The advantages and disadvantages of each method are brought out allowing us to define which method is better for each feature. For example, laser scanning is a better tool for evaluating the surface quality of a surface, while for testing the flatness of the same surface, manual measurement combined with the statistical regression may better identify the slope of such surface.

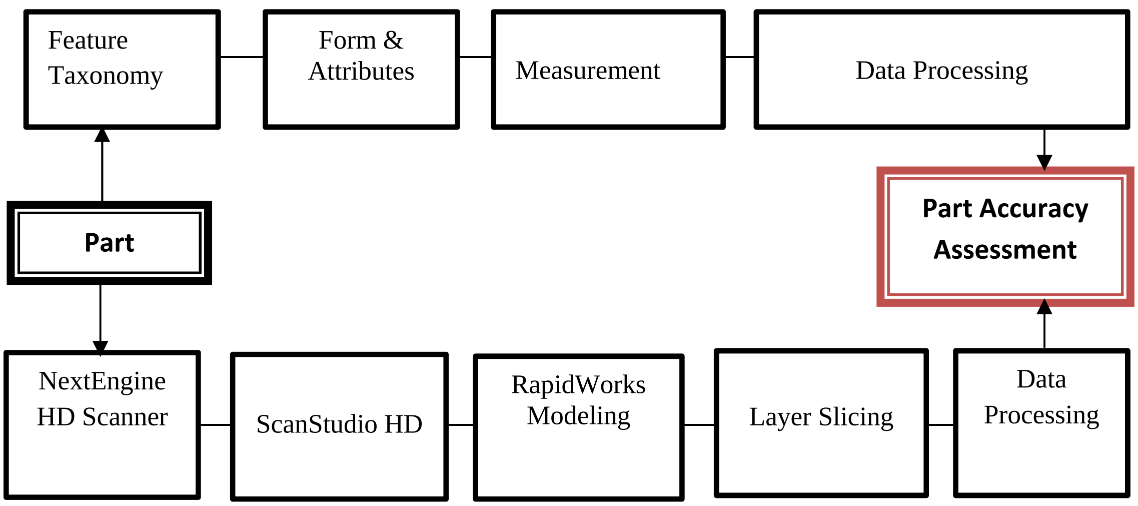


Figure 1. Hybrid method: Evaluating the accuracy of different features in a part by manual or laser scanning method

I. Manual Method

In the manual method, all features in a part are identified based on the existing feature taxonomy. For example, a box with a through hole is broken down into a box and a cylinder.

Then, for each feature, all related forms and attributes are identified. For example, a box needs to be tested regarding the flatness, perpendicularity, and parallelism of the faces and a cylinder needs to be tested regarding the cylindricity. An appropriate measurement tool is used to measure each of the forms, and finally, a statistical method evaluates the accuracy of the features in the part.

i. Feature Taxonomy

Feature taxonomy is a hierarchical tree structure that helps classifying features. Prismatic features, rotational features, and sheet metal features are the most common in feature taxonomy classifications. Gindy's Form-Feature Taxonomy shows prismatic subtractive features using orthogonal directions in which a feature can be approached (Gindy, N. Z., 1989). Owudunni did an extension to that classification and included in it the prismatic additive features and subtractive and additive rotational features (Owodunni, O., Miladenov, D., Hinduja, S., 2002). Figures 2-4 show the classification of the rotational, prismatic, and sheet metal features.

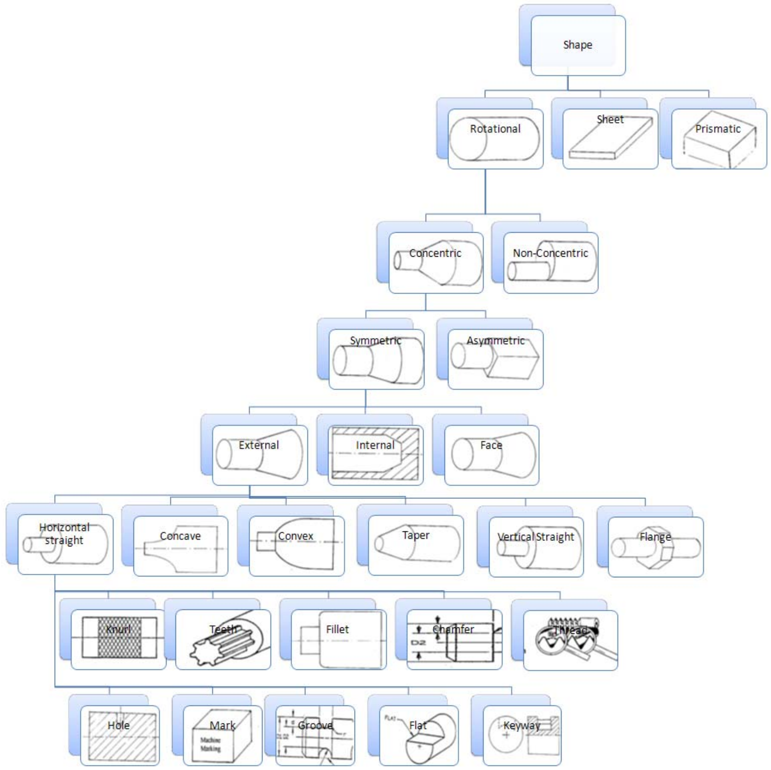


Figure 2. Rotational feature taxonomy

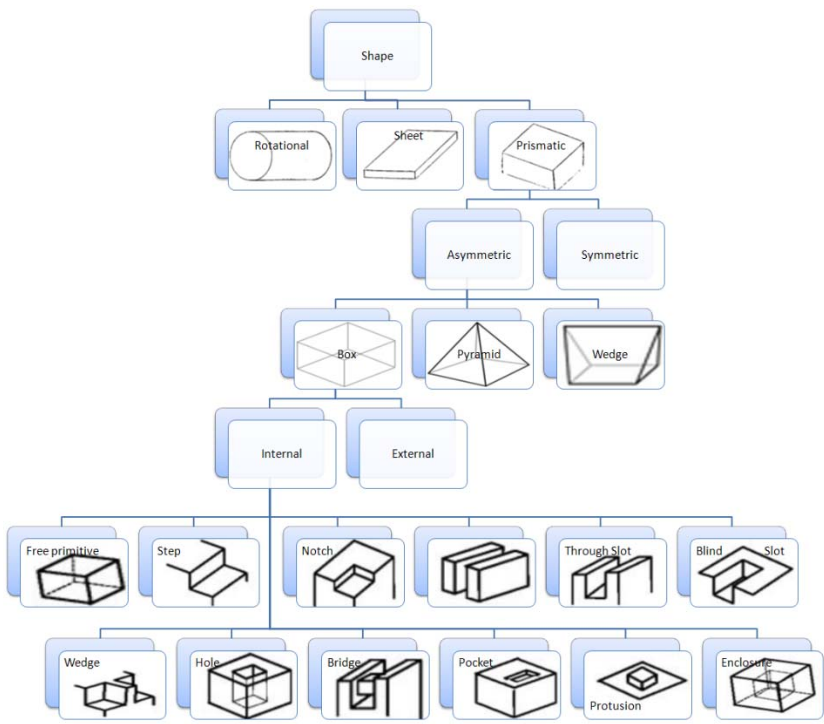


Figure 3. Prismatic feature taxonomy

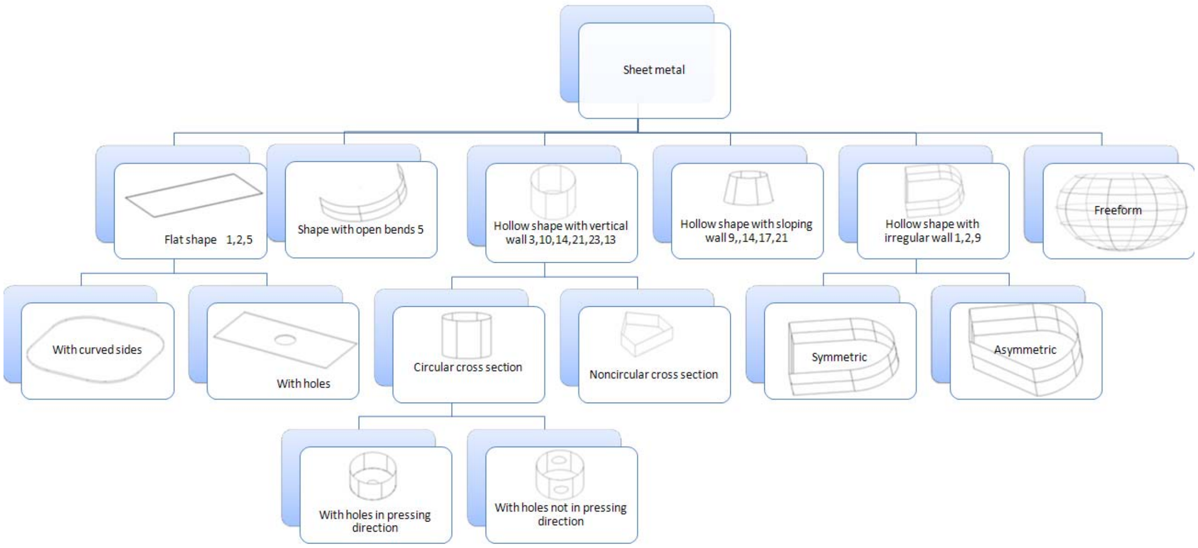


Figure 4. Sheet metal feature taxonomy

ii. Form and Attributes

To evaluate each part, its features need to be broken down into the most primitive level as identified in the above taxonomies. Then, a method/tool needs to be identified to measure the accuracy of that feature. Geometric Dimensioning and Tolerancing (GDT) defines a list of attributes which includes straightness, flatness, circularity, and cylindricity, as the form angularity, parallelism, perpendicularity as the orientation, and concentricity, symmetry, and position as the position attributes. (Figure 5).

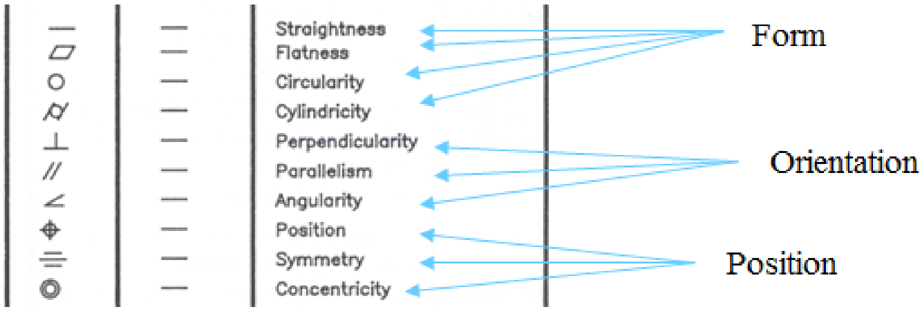


Figure 5. Form, orientation, and position attributes (Nee, J.G., 2010)

In this study the following attributes are used to evaluate the accuracy of the selected features in each part:

- Straightness is defined as a two-dimensional geometric tolerance that controls how much a feature can deviate from a straight line. To measure the straightness of a line we must verify that the line does not curve along its extension.
- Flatness is defined as a three-dimensional geometric tolerance that controls how much a feature can deviate from a flat plane. To measure the flatness of a surface it is necessary to place the item on a flat plane and then to measure the deviation of the surface from the flat plane.
- Circularity is a two-dimensional geometric tolerance that controls how much a feature can deviate from a perfect circle. To measure circularity it is necessary to place the item in a rotational basis or support and verify that the radius is the same along its circumference. Cylindricity is a three-dimensional geometric tolerance that controls how much a feature can deviate from a perfect cylinder. Measuring cylindricity is necessary to measure the circularity along the item extension.
- Angularity is a three-dimensional geometric tolerance that controls how much a surface, axis, or plane can deviate from the angle described in the design specifications.
- Perpendicularity is a three-dimensional geometric tolerance that controls how much a surface, axis, or plane can deviate from a 90 degree angle.
- Parallelism is a three-dimensional geometric tolerance that controls how much a surface, axis, or plane can deviate from an orientation parallel to the specified datum.

iii. Feature Measurement

For the measurement of attributes, a variety of tools are being used as specified in Figure 6. For the manual method of this study, generally contact methods such as dial indicators and

CMMs (Coordinate-measuring machines) were used. When needed, customized tools were designed and developed as well.

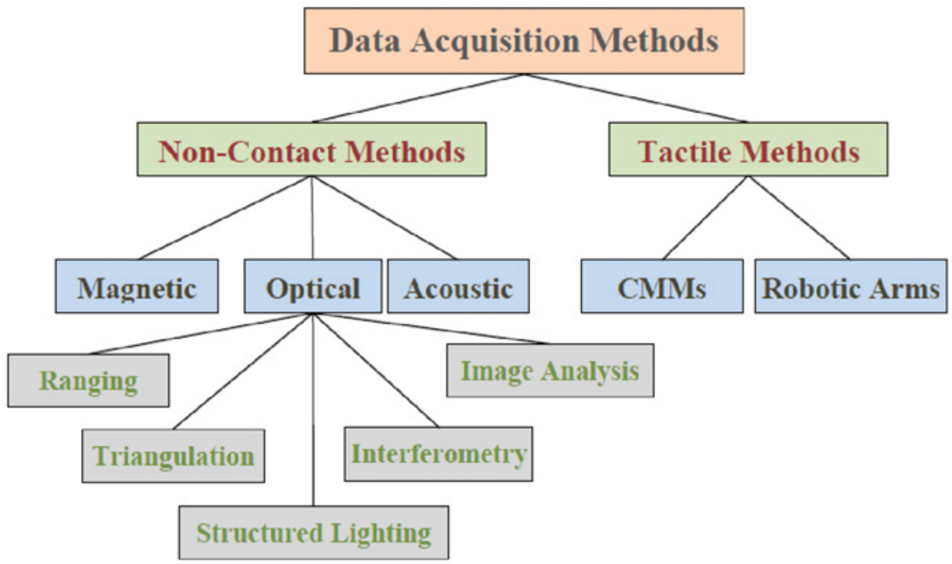


Figure 6. Data Acquisition Methods

II. Laser scanning method

In order to measure the accuracy of a laser scanned 3D model in a CAD program, first determine the types of error that may exist. These inaccuracies are based on the original dimensions of the part and tend to vary with different geometric features. For instance, the dimensions of a cylindrical hole in a part may vary in depth, diameter, and location with respect to the part, while the basic prismatic shape may vary in overall length, width, and height. Due to the abundant types of inaccuracies, it is necessary to develop a method of categorizing the different forms of errors that may be involved in each feature-based classification.

Measurement analysis on CAD software can be approached in the same manner as it is performed on an actual physical model. In order to accurately determine the amount of error, numerous measurements are needed at different points along the object. This data can be analyzed statistically by calculating the average and standard deviation of all data entries. The final value will be compared with the original dimension of the part and the percent differential can then be calculated, thus determining the amount of error within that specific dimension of the model.

Other properties, such as volume, surface area, and surface finish, have calculation methods based on the type of software being used. Volumetric error can be calculated through the use of Boolean operations. When two 3D models are available, they can be aligned together via a datum point or surface. Once aligned, Model A can be subtracted from Model B and vice-versa to determine the solid differences between the parts. Although seemingly simple, problems can occur when alignment is not properly justified. Alignment issues can easily offset the overall results of the dimensional analysis if matching features are not properly assembled. This situation also applies to cross sectional area analysis. If the layers aren't cut at similar positions on the models, the different calculations will be inaccurate.

In this study, NextEngine HD scanner and ScanStudio software were used to scan a part. Then, the model had to be exported to RapidWorks to be edited and imported into SolidWorks to be saved as the desired CAD format. To measure the cross section of the middle areas of a 3D model, an adaptive layer thickness slicer software was also developed in VP inside Inventor Autodesk. Figure 7 illustrates the data flow from the physical part to a computer model along with the software used and the middle file formats.

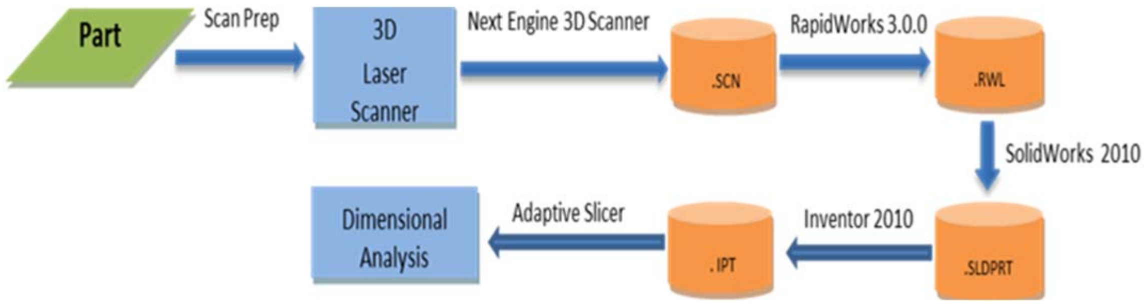


Figure 7. Data flow from physical part to digitized model

Different CAD formats from the part in solid, surface, and wireframe formats were used to evaluate the part's dimensional accuracy in four categories as shown in Figure 8.

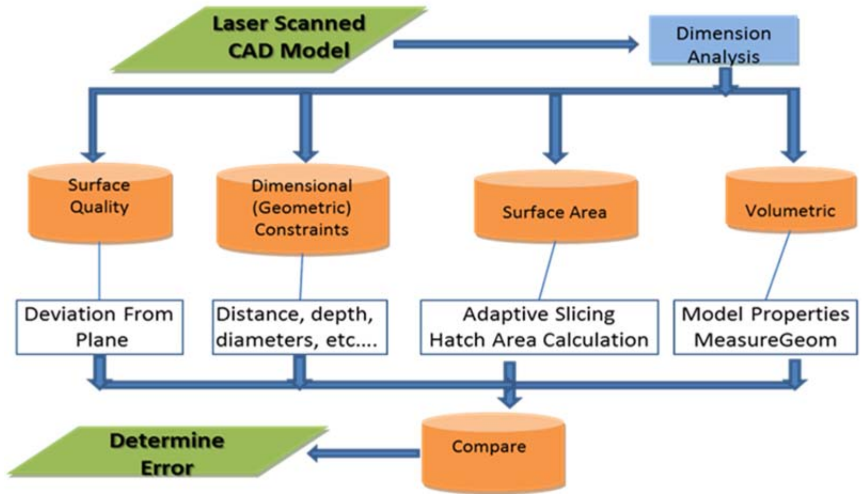


Figure 8. Four different error calculations from the digitized model

3. Case Study

Considering the basic features and the types of error that could occur, sample parts that can include a variety of features were designed: an overall prismatic part with a cylindrical blind hole feature and a filleted edge (Figure 9). The parameters were set at an overall prismatic part equal to 4"x3"x3", cylindrical blind hole equal to 1" diameter and 1" depth, and edge fillet with a 1" radius. The part was then manufactured with the Zprinter 450 3D printer. For structural integrity the part was coated with Zbond101.

3.1. Manual Method

For the manual measurement method a Mitutoyo dial indicator was adapted and a custom designed tool made it compatible with a 3 axis Bridgeport CNC. The straightness and flatness of the moving table were verified before the test. The selected part was divided into primitive shapes, resulting in two prismatic and two rotational figures. The surface of the side was divided into squares of 0.1x0.1 inches. The part was placed and fixed on the moving table with the desired surface on the top. The milling head was moved down until the gauge head of the dial indicator touches the surface of the part. To allow for positive and negative deviation the head was moved down an additional one hundredth of an inch so that the dial indicator read -0.1. The CNC machine was set to zero in the initial position. The head of the CNC machine was displaced by -0.1 inches along the “z” axis into the part before distance was recorded. Starting with “x” and “y” both set to zero, data was then collected. Then the “x” and “y” were displaced by 0.1 inches to obtain all the required data. The data acquired was input into an excel spreadsheet to obtain a graphic that allowed to analyze the surface.

3.2. Laser scanning method

A NextEngine 3D Scanner HD was used in order to create the scan file of the manufactured part. The part was positioned on the scanning platform and scanned a full 360˚ view at a 12 division scan, wide range and 500 points per square inch. The part was then rotated such that the two faces not in view of the scanner, one making contact with the base and the other facing up, could be captured. Another 360˚ scan was then performed at the same settings. The scans were trimmed as to remove the excess data points surrounding our part. Excess data enclosed the stand and any supports used during the scan process. Once trimmed, the two scans were aligned to make a more complete image of the part.

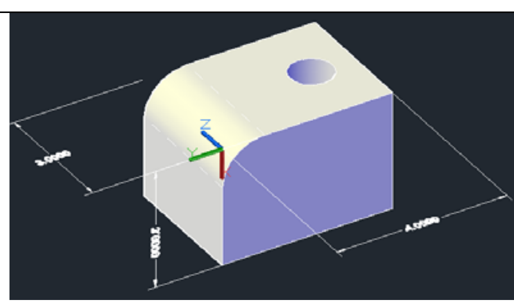
It became obvious that the scanner had not obtained full views inside the hole feature of our part. The part was then repositioned on the platform with a slight tilt in order to specifically scan the hole feature. This process was continued multiple times to obtain the views needed of the hole to complete the model. Upon the completion of the model part, the file could then be exported into RapidWorks software.

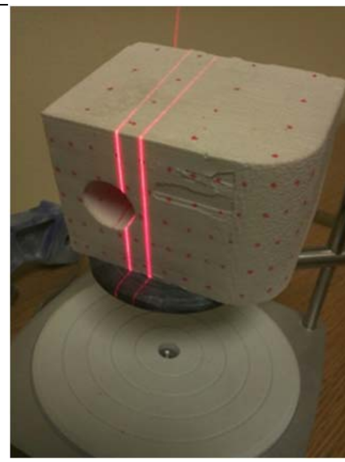
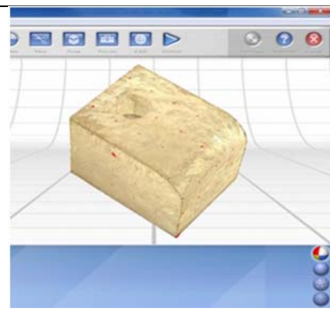
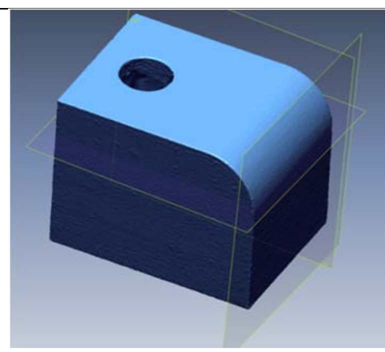
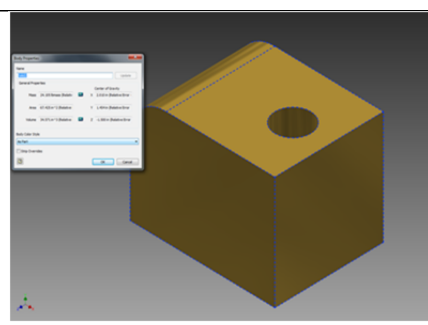
RapidWorks is used to create the file solid model required for analysis. It helps to reduce some of the scanned surface errors by filling in holes that the scanner did not capture through simplifying and optimizing the mesh for downstream software. Once all the minor surface errors are repaired, the file can be transformed from a scanned image and mesh into the solid model.

Upon the creation of the solid model, the file can be exported into SolidWorks. SolidWorks software enabled us to create a multitude of usable formats, such as STL, SAT, and STEP files. These formatted files allow us to use other software such as Inventor, an adaptive slicer, or AutoCAD. The file created needs to be safe as a .STEP file.

The file is then transferred into Inventor 2010 using the .STEP file created while saving in SolidWorks 2010. This now allowed the measurements and Boolean operations to be performed on the new file. To observe the differences in areas between the scanned model and original, a simple A-B and B-A Bollean operation will create a solid mold of the difference in volume. AutoCAD can then calculate the volume. The file can then be passed to the adaptive slicing software used to create profiles at different set dimensions.

The sliced layers in AutoCAD are then used to measure the different distances of the scanned model. The fillet, hole diameter, overall sizes, and distances are measured and input into excel for data processing. These findings will then be compared to the findings of the manual method.

Case study CAD Model	

3D Scanning of the part fabricated by the Zprint 3D printer	
Scanned file in Scanstudio	
Model in RapidWorks after Solid Formation	
Model in Inventor	

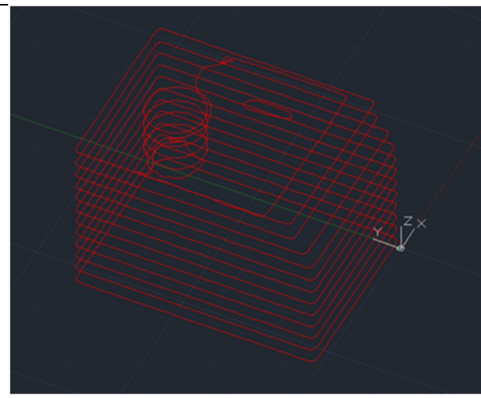
Sliced model simulation	

Figure 9. Different stages of the CAD data conversion

4. Results

4.1. Manual method

A: Flatness

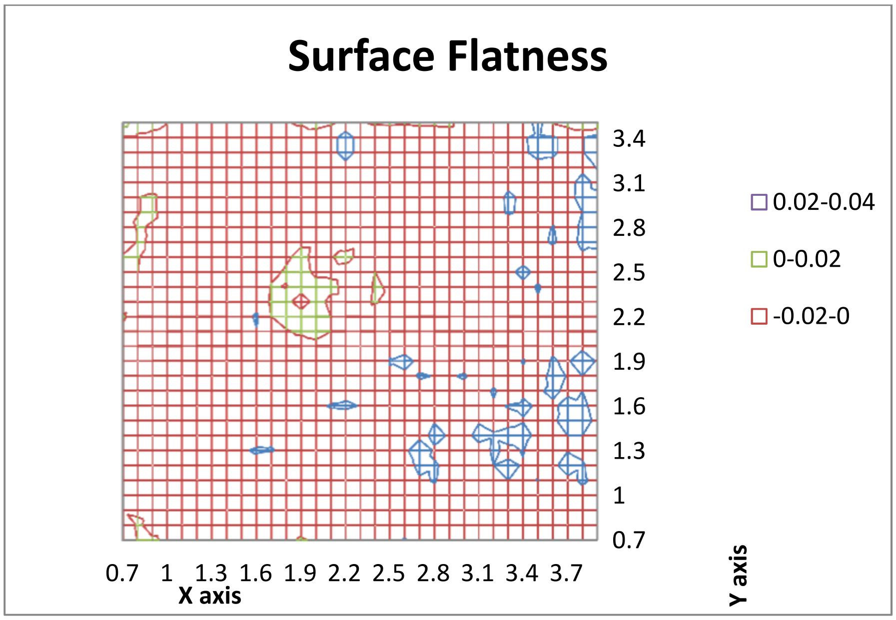
In order to evaluate the error in the fabricated part using the manual method, the data related to the flatness, straightness, and cylindricity of a sample part were collected. In order to calculate flatness the dial indicator and CNC machine were used to collect over 1000 points each at an equal distance from each other. To ensure the capture of all the hills and valleys of the surface (bilateral deviation), the dial indicator zero level (neutral position) were set in a half compressed position. Each of the points read a slightly different Z value having a maximum value of + 0.0898 inches, a minimum value of -0.038 inches, and a standard deviation of 7.64051E-05. All values that were positive were used to calculate the total volume between top surface and zero level (all hills on the surface). The process was then repeated for the negative numbers to get the total volume beneath zero. Also, the total volume of hills and total volume of valleys were combined and divided this total volumetric error by the area of the surface to get a flatness percentage.

Total volume error (in^3)	0.1191425
Deviation from Flatness (in):	0.010910485
Percent error	1.09%
Std.Dev	7.17837E-05
Average (in)	0.000102709
Max (in)	0.0898
Min (in)	-0.038

(a)

Total Volume Valleys (in^3)	-0.11116
Total Volume Hills (in^3)	0.0079825
Negative Deviation from Flatness (in)	-0.010179487
Positive Deviation from Flatness (in)	0.000730998
Percent Error Valleys	1.02%
Percent Error Hills	0.07%

(b)



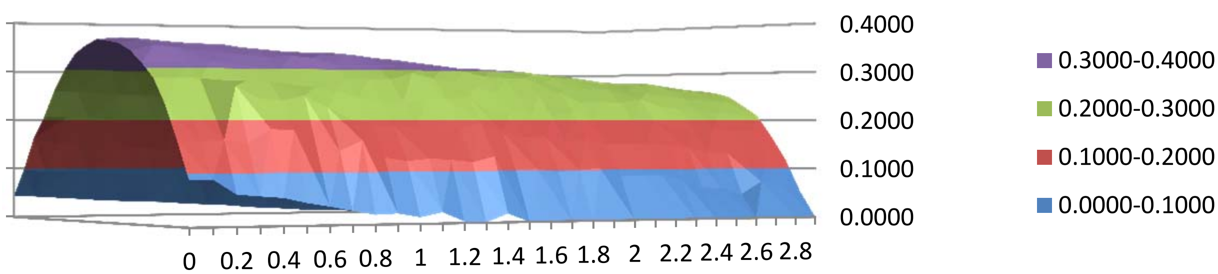
(c)

Figure 10. Height deviation measurement (a), volumetric deviation measurement (b), and height contour (c) of the flat surface data collection

B: Cylindricity

To calculate the overall accuracy of a fillet, the dial indicator was positioned perpendicular to the surface touching point. Measurements at 0, 30, 45, 60, and 90 degrees were conducted. In order to analyze the data, it was flattened out (projected) so that it can be compared to the original CAD surface. Similar to flatness test, the total volume of hills and valleys w calculated. The percentage error from perfect cylindricity was surprisingly high (12 %). Further investigation confirmed an upward slant. Similar slope was observed from the laser scanned measurement as well.

(a)



Total Volume error (in^3)	0.068356
Deviation from Cylindricity (in)	0.126198
Percent Error	12.62%
Std. Dev.	0.014157
Average (in)	-0.00254
Max (in)	0.0295
Min (in)	-0.0425

Total Volume error Valley (in^3)	-0.04723
Total Volume error Hill (in^3)	0.021127
Negative Deviation from Cylindricity (in)	-0.08719
Positive Deviation from Cylindricity (in)	0.039005
Percent Error Valleys	8.72%
Percent Error Hills	3.90%

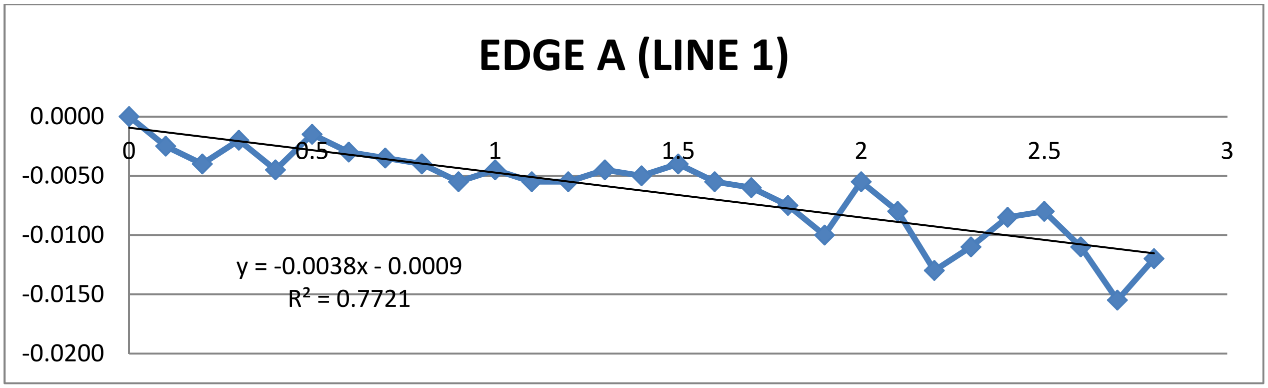
(c)

(b)

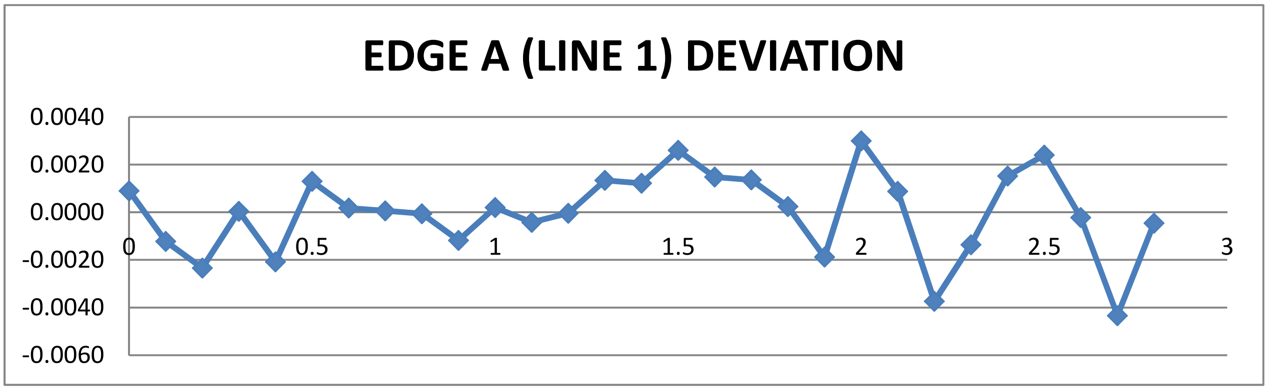
Figure 11. Collected data including surface roughness and an obvious slope (a), height deviation measurement (b), volumetric deviation measurement (c)

C: Straightness

To evaluate the straightness of an edge, data points on two lines of data orthogonal to each other and as close to the edge as possible were collected. After processing the data, similar to fillet, a constant rise was observed. The slope is an accuracy error different from natural horizontal surface roughness hills and valleys. In order to differentiate between the accuracy and surface roughness errors, the best fit line was calculated. Then the data points were rotated back in the amount of slope to measure the straightness of the edge error.



(a)



(b)

Figure 12. Trend line (accuracy error) (a) and rotated data point (surface quality error) (b)

4.2. Laser Scanner method

A: Sliced model comparison

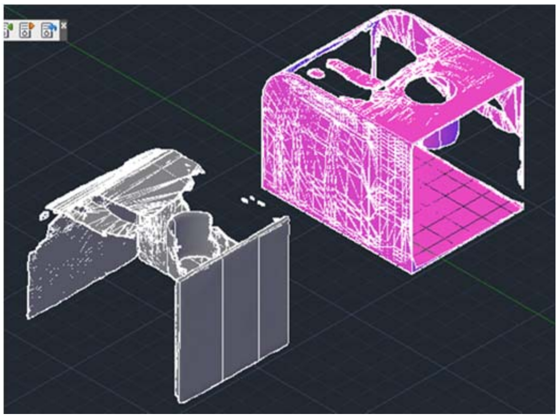
To compare models, the newly developed adaptive slicing program was used (last step in Figure 9). This software slices each individual model for any specified thickness and axis. The script files created from the program can be imported into AutoCAD and analyzed as a layered 3D model or as individual layers. After using this tool for both original and scanned models, layers from both models were overlapped and surface quality, dimensional accuracy, and locational errors were evaluated.

	Overall Cubic Shape			Fillet		
	Length	Width	Height	Radius	Starting Point	Ending Point
	4.0941	2.9940	2.9830	1.0805	1.8983	2.9655
	4.0978	3.0000	2.9908	0.9790	1.9475	3.1670
	4.0877	2.9840	2.9800	1.0150	1.9480	3.1070
	4.0790	2.9828	2.9676	1.0100	1.9200	3.1525
	4.0809	2.9907	2.9870	1.0890	1.9630	3.0740
	4.0520	3.0085	2.9480	1.0890	1.8550	3.0690
	4.0757	2.9787	2.9860	1.1280	1.8540	2.9890
	4.0520	2.9939	2.9960	1.1065	1.8990	2.9835
	4.0860	2.9890	2.9561	0.9955	2.0420	3.0500
	4.0940	2.9850	2.9875	1.0765	1.9020	3.0410
	4.0799	2.9907	2.9782	1.0569	1.9229	3.0599
	0.016314	0.008889	0.015774311	0.0519732	0.055784502	0.077662
	4	3	3	1	2	3
	1.998	-0.31133	-0.726666667	5.69	-3.856	1.995

Figure 13. Original vs. scanned deviation for different slice levels

B: Volumetric difference

Autodesk Inventor was used to apply Boolean operations between the original solid model and scanned model generated solid model. Inventor’s method for finding the difference in volume is not very user friendly. Both parts need to be in a separate .ipt file. Then, each file needs to be imported into an assembly file. Within the assembly file, they need to be aligned via a specific datum point. After aligning, the assembly file needs to be saved and then opened as a new parts file. Once open, the derive function is used and the assembly file is imported. At this point, the Boolean operation is used to subtract the parts from each other. Afterwards, the total volume remaining can easily be calculated. The operation is implemented for both (Original – Scanned) and (Scanned – Original) CAD files (Figure 14).



Category	original part in^3	original - Scanned	Scanned - original
Volume	34.571	0.4700	0.8919
% error		1.3595	2.5799

Figure 14. Volumetric difference between the original CAD and scanned CAD files

5. Conclusion and discussion

In this research a hybrid manual/laser scanner-based method was used to evaluate the accuracy of the produced parts. For the manual data collection method a special tool was designed to continuously hold the dial indicator perpendicular to the physical part. For the laser scanner-based method, software was developed to slice scanned models in the adaptive layering fashion. In order to process and evaluate a part’s accuracy, statistical and CAD software were used.

The laser scanner and the manual method both had their benefits. The manual method was used because it would have greater accuracy than the laser scanned method. The laser scanner method would require polishing or smoothing thus changing the data collected while the manual method could be analyzed statistically in Excel. While the laser scanner is less accurate, it could be more accurate by updating the program from a 32 bit operating system to a 64 bit operating system. The benefit of the laser scanning method is that one can work on very complex geometries.

Another benefit of the manual method is that different errors can be differentiated and separated. In this study the manual method and statistical line fitting showed that, in addition to the surface quality deviation error, there was a trend error in the data; as the part got closer to the front right side of the printer it was steadily increasing. Further observations clarified that the trend error is caused by the build orientation; as the printer lays down a new layer of powder it drags the old binder and powder from the back of the printer to the front of the printer. The print head will also cause a trend error as it pulls the binder from left to right. This problem might have occurred only for the specific machine used in this study and cannot be simply extended to this model of machine. The surface quality error has its roots in the printer dpi, binder dpi, and the Z-bond applied after the printing process.

References

Bi, Z. M., Wang, L., (2010). Advances in 3D data acquisition and processing for industrial applications. *Robotics and Computer-Integrated Manufacturing, 26 (5),* 403-413.

Cheng., J.T., Zhao, W. L., Zhao, C., Xie, X. D., "*The Research of Data Points Quality Assessment Method in Reverse Engineering*", Key Engineering Materials - Vol. 419-420 - 2009 - pp. 445-448.

Gindy, N. N. Z. (1989). "*A hierarchical structure for form features*", International Journal of Production Research, 27 (2), 77-99.

Narayanan Namboothiri V. N., Shunmugam, M. S., (1998). “*Function-oriented form evaluation of engineering surfaces - The L_1 solution to an overdetermined linear system*” Precision Engineering, 22, 98-109.

Nee, J.G., Fundamentals of Tool Design, 6th edition, Society of Manufacturing Engineers, 2010.

Owodunni, O., Miladenov, D., Hinduja, S., “Extendible Classification of Design and Manufacturing Features”, CIRP Annals - Manufacturing Technology 51(1):4 (2002).

Várady, T., Martin, R., and Cox, J. (1997), “*Reverse engineering of geometric models - an introduction*”, Computer-Aided Design 29 (4) , pp. 255-268.

Weber, T., Motavalli, S., Fallahi, B., & Cheraghi, S.H. (2002). “*A unified approach to form error evaluation*”, Journal of the International Societies for Precision Engineering and Nanotechnology, 26, 269–278.

Wu, X. M., Yu, G. B., Li, G. X., Shan, D. B., 2011, “*Error Analysis and Precision Evaluation of Reconstructed Surfaces in Reverse Engineering*”, Key Engineering Materials, 460-461, 581.

Yau, H.T.; "*Evaluation and uncertainty analysis of vectorial tolerances*"; Precision Engineering, 20, pp. 123-137, 1997.