A PRELIMINARY INVESTIGATION ON METROLOGY ASPECTS IN RAPID PROTOTYPING

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ABSTRACT
The objective of this study is to investigate dimensional and form accuracy in rapid prototyping. Part accuracy has a direct impact to applications of rapid prototyping technology. In addition, understanding the error behavior can guide error compensations and may provide feedback to improve the process. In this study, different geometric models were arranged to test possible causes for geometry errors. Solid models were built by a multi-jet modeler, measured by mainly a coordinate measuring machine, and dimensional and form errors were analyzed. Major results show that (1) shrinkage errors are not isotropic, but approximately linear to the part size, (2) hollow models generally have better accuracy than solid counterparts, and (3) form errors seem to be proportional to the part size. The adopted approach may be suitable for error characterizations and modeling to other rapid prototyping processes. However, the challenge is to use limited models to gain maximum characteristic information.

INTRODUCTION
Rapid prototyping is a technology in which physical objects are directly fabricated from Computer-Aided Design (CAD) data sources. All types of this technology are similar to each other in that first a 3D solid model is generated in a CAD package, which is then exported in Stereolithography (STL) format and sliced to many layers of very small thickness and transferred to rapid prototyping (RP) systems [Cooper 2001]. 3D prototypes are then built layer by layer by adding and bonding consecutive layers. Liquid-based RP constitutes processes such as Stereolithography Apparatus (SLA), Fused Deposition Modeling (FDM) and Multi-Jet Modeling (MJM). In SLA, a photosensitive liquid turns into a solid polymer on exposure to a laser. MJM is a phase change Inkjet technology which consists of a print head having large number of jets through which a molten wax-type material is squirted only where necessary and then solidified. FDM consists of a movable head which deposits molten material. Laminated Object Manufacturing (LOM) is a solid based process in which sheets of build material are cut with a laser and glued to the previous layers. Selective Laser Sintering (SLS) and Three Dimensional Printing (3DP) are powder based. Some of the processes require support structures which are usually generated.
automatically employing specialized software tools [Pham and Dimov 2001]. Rapid prototyping has diverse applications. Concept models can be used for visual and physical descriptions of final models and also used for fit test applications. Prototypes can also be used for making patterns in investment casing and in rapid tooling. By employing RP techniques it is possible to begin test programs such as engineering analysis on physical models complementing computer aided engineering data [Pham and Dimov 2001]. In automobile industry, RP is used to produce models for components such as engine blocks and automobile panels. Many indirect rapid tooling methods can also be used in manufacturing to produce functional parts. In medical fields, RP models has been used to fabricate master patterns such as implants, and in making medical instruments including retractors, scalpels and many others.

Models made by some RP technologies are used for patterns in investment casting [Cooper 2001]. Since the pattern in investment casting directly affects final part quality, dimensional and form accuracy are critical. In investment casting, e.g., part tolerances for a linear dimension up to 1.0" is ±0.005" and flatness for a section thickness of 0.5" to 1.0" should be in the range of 0.004" to 0.006" [Simmons 2000].

Many factors influence accuracy in rapid prototyping and researchers have studied various parameters in different processes that effect surface finish, accuracy and quality of prototypes. Paul and Voorakarnam [2001] studied the source of surface roughness in LOM process. Results showed that the orientation angle and paper thickness are statistically significant and in-process control of prototype surface roughness may be possible by gaining greater control of the working distance during processing. Reeves and Cobb [1996] studied surface finish using nine different combinations of rapid prototyping processes and materials, and deduced that surface roughness generated is the cumulative effects of layer thickness, layer profile, and layer composition. Anitha et al. [2001] studied influences of various process parameters on the quality characteristics of prototypes produced by FDM using Taguchi technique. The objective was to minimize average surface roughness values (Rz) by studying significance of parameters such as layer thickness, road width, and head speed.

Layer thickness was found to be the most significant one among all factors. Reeves and Cobb [1996] investigated surface roughness of SLA and developed a model to predict surface roughness for large variety of orientation angles.

Studies have also been conducted regarding the best part build orientations and effects of various build methods on accuracy of different processes. Allen and Dutta [1994] developed a method for automatically computing the support structure for parts in layer manufacturing, and then deciding the best part orientation. Williams et al. [1996] investigated into the effects of various build styles and build parameters in SLA on the performance measures of dimensional accuracy, surface roughness and build time. Rettanawong et al. [2001] developed a part-build orientation system for RP by considering the minimum volumetric error encountered during part building. Cheng et al. [1995] also developed a procedure for optimizing part-building orientation in SLA by assigning weights to various surface types affecting part accuracy. Sreeram and Dutta [1994] developed a method to determine the optimal orientation based on variable slicing thickness for a polyhedral object.

Use of coordinate metrology has been proved to be a powerful tool in analyzing prototype accuracy. Tucker and Kurfess [1999] investigated the use of three-dimensional data analysis in verification of rapid-prototype parts. Coordinate metrology and laser scanning devices were used. Twists, warps and deflections visible in plots of point to model deviations provided insights into the defects characteristics of the SLA process that cannot be obtained by other means. Shellabear et al. [1999] determined the levels of dimensional accuracy and surface quality achievable by several RP processes. CMM was used for dimensional accuracy and laser-scanning microscope was used for surface roughness measurements. It was concluded that common cause of inaccuracy is non-optimal scaling and could be improved by using different scaling factors in X, Y and/or Z directions.

Several studies have been conducted by using finite element methods to analyze the shrinkage behavior, since shrinkage is a common factor for model accuracy in rapid prototyping processes. Bugeda et al. [1995] applied finite element method to analyze the distortion caused by shrinkage effect, and to
simulate the deformation of a built part. Huang et al. [2003] developed a dynamic finite element code to simulate shrinkage effects in constrained surfaces in an SLA system and verified the system's performance. H-4 diagnostic parts were simulated, and compared for different drawing paths, showing that contour-out path planning is the best plan.

Rapid prototyping is a thermal or chemical related phase-change process, and thus, shrinkage is one of main concerns in part accuracy. In addition, there are other factors that may influence shrinkage behavior, and consequently model accuracy. This experimental study employed geometric models, designed, built, and measured, to investigate dimensional and form errors in rapid prototyping.

EXPERIMENTAL PROCEDURES

To study dimensional and form accuracy in rapid prototyping, following experiments were designed and conducted. Solid geometric models were constructed and arranged by AutoCAD, and further exported to stereolithography (stl) files with the highest facet resolution. The stl files were transferred to a multi-jet modeler, ACTUA 2100 from 3D systems, to fabricate designed prototype models. ACTUA 2100 has a resolution of 0.0033", 0.0025", and 0.0015" for x (head moving direction), y, and z (height), respectively. The build material used was a wax-type thermopolymer, THERMOJET 65 from 3D Systems. Prototype models were then measured by a coordinate measuring machine (CMM). Brown & Sharpe MicroVal PF-, with an 8 μm (0.0003 in) volumetric performance and 2 μm repeatability (ASME B69.4.1-1997). Precision gage blocks were also used to verify the CMM accuracy. All measurements including all following tests were conducted nine times to obtain average and standard deviation values plotted in the figure. Figure 1 plots relative measurement errors of different sizes of the blocks, confirming the maximum error is around 10 μm. As to be shown later, the prototype models have errors over 120 μm, 10 time greater than CMM, and thus, using the CMM to evaluate the model accuracy is adequate. In addition, an optical microscope was used to acquire dimensional information for small-sized features. Required number of measuring points was determined by increasing the number of points until the measurement output (e.g., flatness) approaches a constant. For example, for surfaces of 1" cubes, the number of measuring point was about 20. Distance between two features (e.g., plane-plane) was used for dimension determinations. Different probe orientations were necessary to construct planes at different directions, e.g., tilted 45° for vertical planes. Error due to probe orientations was also evaluated using precision gage blocks, maximum ~10 μm. Dimensional and form errors were further analyzed and relative errors of different models were compared.

![Relative Error vs Nominal Dimension](image)

**FIGURE 1. MEASUREMENT ERRORS OF THE CMM BY USING PRECISION GAGE BLOCKS.**

Different groups of models were arranged and fabricated to investigate error sources and characterize the error behavior. To examine location effects (possibly due to mechanical drive imperfection), several 1-in. cubes were arranged at widely spread positions on a platform. Cube arrangements were shown in Figure 2 with relative coordinates (bottom center of cubes to the point O) given in Table 1. Relative coordinates of O to the platform corner are approximately (1.2", 1.7", 0.44") for different dimensions (1", 3", and 5") were produced and measured to investigate size and direction effects on dimensional and form accuracy. Hollow models (with shell thickness of 0.2") were also tested, and relative errors in dimension and form were compared with solid counterparts. RP models used for investment casting patterns (or concept models) are not required to be solid, and thus, material saving can be greatly achieved by employing hollow models. Shrinkage characteristics in RP are possibly direction dependent, and moreover, error in one direction may be affected by size (or area) in other directions. Thus, models with the
same height (3"), but different lengths (or widths) while fixing width (or length), 1", were arranged and fabricated. Relative errors in height of models with different lengths (or widths) were then compared. Figure 3 shows an example of models to study length effect on the height error. To investigate errors at small sizes, parallelepipeds with varied widths (ranging from 0.003" to 0.5"), but constant length (1") and height (0.05" or 1"), were also produced to examine machine resolution and to evaluate errors at small sizes. Similarly, parallelepipeds with fixed width and height, but varied lengths were also tested and compared. For form accuracy, flatness of different cube-models were measured and compared against their nominal side dimensions. In addition, cylinders with different diameters (1" to 5") were also used to evaluate roundness errors from CMM data.

![Figure 2. Arrangement of 1" cubes for examining error due to location.](image)

![Figure 3. A model for assessing the effect of size at different directions on accuracy.](image)

**RESULTS AND DISCUSSION**

**Dimensional Accuracy**

**Location effect.** Measurements of nine 1-in cubes at different locations (Figure 2) were analyzed to evaluate relative errors (% difference between measured and designed dimensions). All measured dimensions including results in the following sections were smaller than designed values (i.e., contraction), and thus, absolute values of relative errors will be consistently used through the text. Figure 4 compares relative errors of length, width, and height of cubes at different locations; corresponding number can be found in Figure 2. Data points are averages of nine measurements (applied to all models in this study) with standard deviation values shown as well. In general, no significant difference between different cubes is noted, however, cubes at lower locations (0.5" z) show smaller errors. For height, relative errors are 0.3% to 0.6% of bottom cubes vs. 0.8% to 0.8% of top ones. For width and length, relative errors are 0.8% to 1.1% of bottom cubes vs. 0.9% to 1.2% of top ones. Further, errors in length and width are in a close range. However, length/width errors are greater than height errors, averagely 0.9% vs. 0.4% for bottom cubes. The above results suggest that prototype models produced are marginally satisfactory in accuracy from investment casting considerations (<±0.5% for 1" dimension [Simmons 2000]). Nonetheless, the deviation may be corrected by shrinkage compensation in RP software.

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FIGURE 4. RELATIVE ERRORS IN DIMENSIONS FOR 1" CUBES MADE AT DIFFERENT LOCATIONS.

To examine process repeatability in rapid prototyping, the small and large cube models (1" and 5") have been duplicated (3 times, similar location), and further measured in dimensions. Results are shown in Figure 5. For 1" model, standard deviations are 0.09% and 0.15% for length/width and height, respectively. For 5" cube, standard deviations are smaller, 0.06% and 0.11% for length/width and height, respectively. Interestingly noted, the variations are smaller than the variations caused at different locations. Because of the high material cost (~$100/lb), only these models were tested against repeatability as upper and lower bound information. It can be expected that smaller variations may occur for hollow models.

FIGURE 5. RELATIVE ERRORS OF THREE 1" AND 5" CUBES FOR REPEATABILITY TEST.

Size and direction effects. Material shrinkage is probably the major geometric error source in RP, and it has been mostly assumed to be proportional to the part size. Dimensions of cubes with different sizes were measured and relative errors compared. Figure 6 plots relative errors of length, width, and height against the nominal dimension of cubes. Relative errors are different between length (width) and height, smaller in height. This indicates that shrinkage compensation needs to be anisotropic which is available in RP software. It is also observed that relative errors are not constant, i.e., error is not linear to part size. However, the difference is not significant. Thus, for practical usage, linear approximation of shrinkage errors in RP may be reasonable and shrinkage compensation would be easier to implement.

FIGURE 6. COMPARISON OF RELATIVE ERRORS OF SOLID CUBES.

Solid vs. hollow effects. 1", 3", and 5" cubes were also built in hollow (0.2" shell thickness), and relative errors were compared with solid counterparts. Figure 7 shows relative errors in width and height for both solid and hollow cubes. It can be observed that relative errors reduce about 25% in the hollow models compared to solid ones. Relative error of width is similar to length error, but greater than that of height as in the solid models.

FIGURE 7. COMPARISON OF RELATIVE ERRORS BETWEEN SOLID AND HOLLOW CUBES.
A simple part (hollow stacked blocks, Figure 8) was used to verify the error behavior established by hollow cubes. Figure 9 plots both measured relative errors of the test part and error curves established from 3 hollow cubes. Measured results are reasonably close to the predictions.

![Diagram of nominal dimensions of a test stacked block (unit: in).](image)

**Figure 8. Nominal Dimensions of a Test Stacked Block (Unit: In).**

![Graph showing relative error trends and measured errors of the test stacked block.](image)

**Figure 9. Comparison of Predictive Error Trends and Measured Errors of the Test Stacked Block.**

**Size effects (cross-direction).** Four blocks with constant height (3") and width (1"), but various lengths (1", 3", 5", and 7", Figure 3), were measured in height by the CMM. Relative errors were compared against block length. Similarly, blocks with various widths, but same height and length, were also compared in measured height. Results are shown in Figure 10, plotting relative errors in height for different dimensions of width or length. It can be noted that width and length do affect the error in height, with a range of 0.1% to 0.9%. Note that for a 3" cube, relative error in height is about 0.7%. If such relationship does exist, it may imply that error compensation for irregular geometry may not be a simple relation.

![Graph showing comparison of relative errors in heights of rectangular blocks with different widths or lengths.](image)

**Figure 10. Comparison of Relative Errors in Heights of Rectangular Blocks with Different Widths or Lengths.**

**Small sizes.** Figure 11 shows relative errors in length or width of small-sized models with 1" height. It is observed that relative errors become rather large when the part size decreased to less than 0.1". In addition, it has also been observed that parts with width (or length) less than 0.03" could not be constructed, rather the parts collapsed.

![Graph showing relative errors at small sizes made at 1 in height.](image)

**Figure 11. Relative Errors at Small Sizes Made at 1 in Height.**

**Form Errors.**

Figure 12 plots flatness values for different cubes, also at different surfaces. The results indicate that flatness errors increase with cube dimensions significantly and are sensitive to the plane directions, top surface being least flat. It is also observed that hollow models result in similar flatness values, though no clear trend.
Figure 13 plots roundness of different sizes of cylinders. It also shows that roundness is proportional to the cylinder diameter. In addition, relative errors in diameter have the same trend as in cube dimensions, increasing then decreasing with sizes.

![Graph showing roundness vs. nominal diameter](image)

**Figure 12.** Flatness at different surfaces of solid cubes.

**Figure 13.** Roundness as a function of cylinder diameter.

Dimensional and form accuracy of prototype models at different sizes/configurations were acquired by CMM, and the results were compared against the size, direction, and solid vs. hollow, etc. Characteristics of geometry errors of the models have been presented and do show some interesting phenomena and trends that may be used to model error behavior for compensation. The focus of this study is not one specific rapid prototyping technology, either an individual machine/material. Rather, the attempt was to use some geometric models to characterize the dimensional and form error behavior for the purpose of improving compensation methods to achieve better accuracy. It is understandable that different rapid prototyping processes may have different error characteristics because of the process mechanisms (e.g., photocuring in SLA and solidification in MUM, etc.). In addition, the machine itself may have some level of variations in accuracy possibly due to the production environment (temperature and humidity, etc.), mechanical drive, and materials, etc. Therefore, the error characteristics from this study may not imply completely the same trend to other rapid prototyping processes. However, the approach taken, using geometric models for error characterizations, is also applicable to other rapid prototyping processes.

**CONCLUSIONS**

This study investigates dimensional and form accuracy of models made by rapid prototyping technology. The attempt is to use some designed models to identify and characterize geometric errors, and thus, feasibly provide a mechanism to improve shrinkage compensation strategy. The approach includes arrangements of geometric models, RP model fabrication by a multi-jet modeler, dimensional and form measurements by CMM and optical microscopy, and analysis of dimensional and form errors. It has been found that (1) model accuracy is not significantly influenced by its location, (2) model dimensions are reasonably repeatable, (3) shrinkage errors are not isotropic, but may be approximated as linear, (4) hollow models give less errors than solid counterparts, and (5) shrinkage error in one direction may be affected by the dimension in other directions.

The results seem to imply that it is possible to use simple geometric models to characterize the error behavior in RP and further used for shrinkage compensation consideration. However, because of high RP material cost, the challenge will be the geometric model design to reduce the number of models needed and, meanwhile, able to deduce required information on error characteristics.

**ACKNOWLEDGEMENTS**

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REFERENCES


