Fast Deviation Simulation for 'Fused Deposition Modeling' process

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Abstract

The paper presents a hybrid experimental/theoretical approach to study the effect of variation due to process parameter change on the dimensional and geometric accuracy of a part built through ‘fused deposition modeling’ process. A theoretical framework comprising of a primitive based fast geometric model and a comprehensive process parameter-geometric tolerance matrix is presented. This framework is tested with help of an experimental setup based on a geometric variation measurement model for major classes for Geometric Dimensioning & Tolerancing (GD&T) tolerances. Finally, a statistical approach based on Taguchi’s design of experiment is utilized to study the effect of commonly used process parameters to establish indicative GD&T tolerance bands for the specific printer class as well as ranking of parameters.

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1. Introduction

Additive manufacturing (AM) process creates 3-dimensional solid parts directly from a computer aided design (CAD) model. This technology encompasses several processes such as stereolithography (SLA), selective laser sintering/ melting (SLS/M), three dimensional printing (3DP) and fused deposition modeling (FDM). Each process differs in the type of material used and in its manufacturing technique. In general, the 3-dimensional solid parts are created by adding materials in successive layers. This technology enables the creation of highly complex solid parts without the need for any conventional or intermediate tooling. AM process allows the manufacture of customised solid parts, both for functional prototypes and end user products, in shorter production time as opposed to traditional manufacturing processes. Low cost and simple machine operation are some of the advantages of this form of manufacturing process.

The AM process has been widely used in the manufacture of functional prototypes, for design aids and testing, customisable parts and in small scale manufacturing environment. However, the process is rarely used in end manufacturing environment.

The AM process lacks the critical information such as process repeatability and consistency of the manufactured products for it to be accepted as a real manufacturing process. In addition, information with regards to the mechanical and geometrical properties of printed parts are important for this process to be used in real production environment (Huang et al. [1]). The issue with process reliability, mechanical properties and dimensional accuracy is more prominent for the FDM process as highlighted by Noy [2].

To address these issues, there is a need to benchmark the performances of the AM processes. Benchmarking can be used to analyse both the mechanical and geometrical properties of printed parts. Wong et al. [3] have broken down the AM benchmarking into three categories:-

- **Geometric Benchmark used for measuring the geometric features of a printed part such as tolerances, accuracy, repeatability, surface finish, etc.**
- **Mechanical Benchmark used for analysing the mechanical properties of printed part such as tensile strength, compressive strength, impact strength, flexural strength, etc.**
Process Benchmark used for establishing process related parameters such as part orientation, infill density, layer thickness, speed, etc.

2. Objective

For the FDM process in particular, research has shown that varying process parameters results in a change in the mechanical properties of printed parts. Sood et al. [4]; Qureshi et al. [5]; Fatimatuzahraa et al. [6]; Ahn et al. [7] have all investigated the effects of varying process parameter such as layer thickness, part orientation, infill density and number of shells and have concluded that variations in certain process parameter have resulted in a significant change in the mechanical properties of printed parts.

However, there is a lack of comprehensive research into how variations in the process parameter will affect the dimension and geometric accuracy. Kumar et al. [8]; Ali & Maharaj [9]; Lužanin et al. [10] have investigated the effects of parameter change on surface quality. Nancharaiah et al. [11] have investigated the effects of parameter change (layer thickness, road width, raster angle and air gap) on the dimensional accuracy and surface quality on specimens printed in accordance to the ASTM D695 standard. Nancharaiah et al. [11] have shown that layer thickness and road width have significant effect both on the dimensional accuracy and surface quality whereas air gap affects the surface quality only.

The objective of this paper is to analyse the effects of variations in process parameter to the dimensional accuracy and tolerance of printed parts for fused deposition modelling process (FDM).

3. Methodology

A systematic methodology to investigate the effects of process parameter change to the dimensional accuracy and tolerance of FDM printed parts is adopted. The methodology is based on full design-manufacture-analyse cycle to ensure repeatability and consistency. The methodology is divided generally in following four steps as follows:

1. Design of a test component to include geometric characteristics which can be referenced to ISO 1101:2005 [12]: Geometric Product Specifications (GPS) – Geometrical tolerancing.
2. Design of experiment according to the number of process parameters and their assigned level of control.
3. Printing of test components and measuring geometric features for dimensional accuracy and surface quality.
4. Analyse measurement results and establish a ranking for process parameters as well as general tolerance capability.

4. Test Component

In existing research, various designs of test components have been created to investigate the dimensional and geometrical accuracy for AM processes in general. All the designs incorporated various geometric features and tolerances as shown in Figure 1.

Each of the test components used varies in size and geometric features. These features range from simple geometric shapes to complex overhang structures. The test component used by Cruz Sanchez et al. [17] was based on a standardised benchmark model for AM processes proposed by Moylan et al. [13] who proposed benchmark model designed with the purpose of evaluating AM’s process capabilities and machine accuracy. The proposed standardised benchmark model included various features such as holes, pins, staircases ramps and cylinders. For a repeatable and consistent measurement it was postulated that test sample have the following desirable features:-

- have simple geometrical shapes;
- require no post treatment or manual intervention and

![Figure 1: Test components by (from top left, clockwise direction): (a) Fahad & Hopkinson [13], (b) Bakar et al. [14], (c) Islam et al. [15], (d) Mahesh et al. [16] and (e) Cruz Sanchez et al. [17].](image-url)
allow repeatability measurements.

Table 1 summarises some of the test components that have been used in the investigation of dimensional accuracy of parts produced by the various AM processes.

Table 1: Comparison of test components

| Authors            | Dimension | Features                  | Process |
|--------------------|-----------|---------------------------|---------|
| Fahad & Hopkinson  | 270 x 50 mm | cylinders, sphere, cubes | SLS     |
| Bakar et al.       | -         | slots, cube, cylinders, rings | FDM     |
| Islam et al.       | 50 x 50 mm | holes                     | 3DP     |
| Mahesh et al.      | 170 x 170 mm | cubes, cylinders, spheres, cones, slots | SLA/SLS/FDM/LOM |
| Cruz Sanchez et al.| 90 x 90 mm | holes, pins, cylinders, ramps | FDM     |

Taking into account the recommendations for a test component and tolerance characteristics stated in ISO 1101:2005 [12], and enabling a fast deviation simulation, the design of the test component for an investigation should:

- not take too long to print,
- include basic geometrical shapes,
- not include structures which require the use of ‘build supports’,
- have a number of small, medium and large features,
- Should be scalable to measure the impact of the part size to deviation
- be easy to measure and
- include similar features to allow repeatability measurements across the same plane.

It is evident from the analysis of the existing test samples that they are not suited for a majority of Smaller FDM printers due to extremely long print times, very small features, and build complexities preventing running a fast deviation simulation experiment.

This paper presents a test component that integrates most commonly used mechanical features (cylindrical and planar primitives) that form majority of static and kinematic couples in a conventional mechanical system. The test component allows size deviation measurement as well as most commonly used geometric tolerances associated with cylindrical and planar couples as summarised in Table 2.

Table 2: Geometric Tolerance characteristics ISO1101:2015 [12]

| Tolerances  | Characteristic | Symbol | Features          |
|------------|----------------|--------|-------------------|
| Form       | Straightness   |        | outer edges, triangle, steps |
|            | Flatness       | □      | surfaces          |
|            | Circularity    | ☺      | cylinders, hole   |
| Orientation| Perpendicularity| ▼      | outer edge, steps |
|            | Parallelism    | □      | triangle, steps   |
|            | Angularity     | ☺      | triangle          |
| Location   | Concentricity  | ○      | cylinders, hole   |
|            | Position       | +      | cylinders, hole   |

The proposed design for the test component consist of a rectangular base measuring 80 (L) x 70 (W) x 10 (H) mm with simple geometric features: triangle, cylinders, cylindrical and square steps and a hole (Figure 2a). The cylindrical features allow the measurement of tolerances such as circularity, concentricity, and position, whereas the planar features allow measurement of straightness, flatness, perpendicularity, parallelism, and angularity in vertical/horizontal plane. Two cylinders of the same dimension allows for repeatability measurements on a same plane and also the feature’s concentricity with respect to the hole centre. The square steps allow for repeatability measurements across the same plane. These features not only allow for repeatability measurements, it also allows for perpendicularity and parallelism measurements. The triangle feature allows for straightness, angularity and parallelism measurements. In total, the proposed test component allows the 37 measurements of eight geometric tolerances and 26 dimension deviations per test piece. The test component takes approximately one and a half hours to print using the Makerbot Desktop standard print settings.

Figure 2: (a) Dimensions, in millimetres, and (b) datum and geometric tolerances for proposed test component.
5. Design of Experiment

Research into the effects of varying process parameter on the dimensional accuracy of parts printed via FDM process have not been thoroughly investigated. Mahesh et al. [16] conducted a comparison investigation between the four AM processes (SLA/ SLS/ FDM/ LOM) whereas Bakar et al. [14] considered varied three process parameters (layer thickness, contour width and internal raster) in investigating the effects on dimensional accuracy. Cruz Sanchez et al. [17] considered three process parameters (layer thickness, raster width and nozzle speed) in his investigation.

To fully understand the effects of variation in process parameters on dimensional and geometric accuracy for a prosumer grade FDM printer, all major process parameters should be taken into account. A detailed list of process parameters must be taken into account to investigate the full effect on the dimensional accuracy and geometric tolerance of printed parts. Furthermore, the effects of scaling on a printed part should also be investigated in order to understand how changes in size/ scale factor of a part effects dimensional and geometric accuracy. The scaling factor allows a wider range of dimensions for similar geometric features.

In view of the above, a list of both quantifiable and non-quantifiable parameters available in a prosumer grade FDM printer were considered for this investigation. This list was compiled from a literature study of previous research work as well as analysis of the print parameter settings available in popular STL file slicing software (Qureshi et al. [5]). The parameters considered and their assigned level of control are shown in All test components were printed on the Makerbot Replicator 2X FDM printer using Makerbot 1.75mm diameter ABS filament. Makerbot Desktop software was used for the scaling and manipulation of the process print settings.

Table 3.

Table 3: Parameters and control levels

| Parameter | Level 1 | Level 2 | Level 3 |
|-----------|---------|---------|---------|
| A: Component size | 64 x 56 mm (80%) | 80 x 70 mm (100%) | 96 x 84 mm (120%) |
| B: Print location | Left | Centre | Right |
| C: Extruder temperature | 218.5°C | 230°C | 241.5°C |
| D: Print orientation | 45° | 0° | -45° |
| E: Travel speed | 120 mm/s | 150 mm/s | 180 mm/s |
| F: Extrusion speed | 7.2 mm/s | 90 mm/s | 108 mm/s |
| G: Platform temperature | 104.5°C | 110°C | 115.5°C |
| H: Peeling temperature | 218.5°C | 218.5°C | 218.5°C |
| I: Layer thickness | 0.16 mm | 0.2 mm | 0.24 mm |
| J: Infill density | 8% | 10% | 12% |
| K: Number of shell | 1 | 2 | 3 |
| L: Infill pattern | linear | hexagonal | moroccanstar |
| M: Infill shell spacing | 0.64 | 0.8 | 0.96 |

6. Results & Analysis

The dimensions and geometric characteristics of the test components (Figure 3) were measured using an optical coordinate measuring machine (CMM) with an accuracy of less than 2 µm and the results were used to evaluate the process performance for all mentioned dimension deviations and geometric tolerances of the 27 test components. The datum scheme for the CMM evaluation is shown in Figure 2(b). Datum A refers to the top surface while Datum C and D are the horizontal and vertical surfaces respectively of the test component. Datum B refers to the innermost geometric shape (hole) of the circular stepped feature. The signal-to-noise (SN) ratio, using the smaller is better formulation, was used to analyse the influence of the process parameters on the dimensions and geometric characteristics. Each of the process parameters were ranked based on the delta SN ratio values, the difference between highest and lowest SN ratio.

Table 4 shows the SN ratio delta values for each of the dimension deviation measured against the process parameters under investigation. The cumulative signal to noise for each of the process parameter value was used to rank them in order of importance. From Table 4, it is seen that the top five
significance process parameters are component size, extruder temperature, platform temperature, print orientation, and layer thickness.

Figure 3: Printed test components, from left to right, (a) 64 x 56 mm (Level 1), (b) 80 x 70 mm (Level 2) and (c) 96 x 84 (Level 3).

Table 5: Dimensional deviation range (mm).

| Dimension | Overall Deviation | Level 1 (80%) | Level 2 (100%) | Level 3 (120%) |
|-----------|-------------------|---------------|----------------|---------------|
| Length    | 1.01              | 0.29          | 0.81           | 1.01          |
| Width     | 0.86              | 0.52          | 0.57           | 0.59          |
| Diameter  | 0.48              | 0.39          | 0.29           | 0.44          |
| 15mm      |                   | 0.19          | 0.14           | 0.15          |
| 20mm      |                   | 0.14          | 0.14           | 0.08          |
| 25mm      |                   | 0.10          | 0.30           | 0.11          |
| Height    | 0.72              | 0.25          | 0.71           | 0.38          |
| 5mm       |                   | 0.20          | 0.65           | 1.44          |
| 10mm      |                   | 2.37          | 0.30           | 0.35          |

From Table 5, as the test components were scaled up from Level 1 to Level 3 control, the largest deviation can be seen in the Y-direction followed by X-direction and the length. The deviation range (Maximum - Minimum) for the remaining dimensional characteristics were relatively insignificant of 0.5 mm and less.

Similarly for geometrical tolerance deviation, Table 6 shows the process parameter ranking for the geometric tolerances based on cumulative SN ratio values. It is seen that the top five significant process parameters are extruder temperature, layer thickness, print orientation, no of shells, and component size.

Table 7 shows the overall geometric tolerance deviation range for all the samples (Maximum-Minimum). This is measured between the largest and smallest characteristic value measured.

It can be seen that parallelism, angularity and position had the largest deviation among the geometric characteristics. This can due to the fact that the test components were scaled by ± 20%. As the component was scaled from 80% (Level 1) to 120% (Level 3), the deviation for parallelism, angularity and position changed by 0.55 mm, 0.71 mm and 1.72 mm respectively. These three characteristics account for almost 36% of the overall deviation for the geometric tolerance.

| Geometric Characteristic | Overall Deviation | Level 1 (80%) | Level 2 (100%) | Level 3 (120%) |
|--------------------------|-------------------|---------------|----------------|---------------|
| Flatness                 | 0.60              | 0.59          | 0.26           | 0.46          |
| Straightness             | 0.65              | 0.55          | 0.65           | 0.55          |
| Circularity              | 0.52              | 0.48          | 0.48           | 0.48          |
| Perpendicularity         | 0.52              | 0.17          | 0.39           | 0.46          |
| Parallelism              | 0.95              | 0.27          | 0.40           | 0.95          |
| Angularity               | 1.10              | 0.17          | 0.21           | 1.10          |
| Concentricity            | 0.21              | 0.13          | 0.16           | 0.20          |
| Position                 | 2.38              | 0.57          | 0.65           | 2.37          |

7. Conclusion

This paper provides a simple, systematic and fast method for evaluating and establishing a baseline quality capability of a FDM printer for dimensional deviation and geometric tolerance deviations. The approach is based on a simple test piece incorporating ISO 1101 compliant geometric primitives for simulating the cylindrical and planar couples, often used in mechanical systems with associated dimension and geometric tolerances.

The research highlights the isotropic nature of the deviations, dependant on a comprehensive list of factors including part geometry, size, and process specific parameters. Any variations in four out of the top five common parameters identified (component size, extruder temperature, print orientation and layer thickness) significantly affects the dimensional accuracy printed parts (37.6% and 37.5% of cumulative signal to noise ratio) whereas platform temperature and number of shells affects only dimensional accuracy and geometric tolerance respectively.

The paper also presents the ranges for dimension deviation as well as geometrical tolerance ranges for the FDM printers. Using these ranges, an estimate of the tolerances and fits as per Table 6: Ranking for geometrical tolerance deviation based on SN ratio (smaller is better)

| Geometric characteristics | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  | K  | L  | M  |
|---------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Flatness                  | 2.61| 1.42| 0.57| 0.88| 2.02| 1.13| 2.2 | 1.18| 0.95| 1.15| 2.46| 2.79| 0.92|
| Straightness              | 0.94| 0.89| 2.12| 1.72| 0.79| 0.79| 1.17| 1.11| 3.03| 1.17| 0.68| 2.58| 0.58|
| Circularity               | 1.64| 1.87| 0.71| 0.50| 0.59| 1.34| 0.33| 0.28| 1.72| 0.86| 0.82| 1.03| 1.83|
| Perpendicularity          | 2.05| 2.16| 0.93| 3.46| 3   | 1.66| 1.24| 0.36| 1.87| 1.36| 3.58| 0.68| 1.85|
| Parallelism               | 1.37| 1.81| 2.93| 3.32| 2.49| 0.93| 2.36| 1.61| 3.07| 1.48| 1.49| 2.92| 1.69|
| Angularity                | 0.47| 1.84| 5.22| 0.71| 2.51| 2.85| 1.45| 2.11| 5.29| 1.72| 2.57| 2.07| 3.03|
| Concentricity             | 3.07| 1.16| 3.91| 1.35| 1.01| 3.09| 1.22| 1.51| 0.59| 1.95| 2.63| 0.51| 2.27|
| Position                  | 2.96| 0.62| 2.80| 2.15| 1.55| 1.04| 3.03| 1.24| 2.48| 1.96| 1.04| 0.72| 2.72|

| Sum                       | 15.11| 11.77| 19.19| 16.07| 13.96| 12.29| 13.00| 9.40| 19.00| 11.10| 15.27| 13.30| 14.89|
| Ranking                   | 5    | 11   | 3    | 7    | 10   | 9    | 13   | 2   | 12   | 4    | 8    | 6    |
ISO268-1:2010 [19] can be made. The dimensional deviation ranges can be used to compensate during the CAD phase for achieving the required manufactured dimensions.

Figure 4: Interaction between process parameters to mechanical and geometrical properties of FDM printed parts.

Quality assurance of an FDM printed part is a highly coupled problem, between process parameters, and mechanical and geometrical properties (Figure 4). Integrated process modelling is needed to simulate the affects that these parameters have on part behaviour. A simplified model taking into account the top four process parameters as presented in this paper can form the initial optimisation problem with potential to bring significant improvements in the mechanical and geometrical behaviour.

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