Effect of part orientation on dimensional accuracy, part strength, and surface quality of three dimensional printed part

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Abstract. Additive manufacturing such as fused deposition modelling (FDM) three dimensional printing machine can deliver complex shapes with fine details in relatively short building time using various materials (albeit mostly polymers in this case). However, the quality of the printed results might vary depending on the set input. The present study aims to investigate the effects of part orientation on dimensional accuracy, part strength, total cost, and surface quality of a three dimensional printed part. Five test specimens were printed on FDM machine with polylactic acid (PLA) as the material by varying the build orientation, i.e. X₀°Y₀°, X₀°Y₀°, X₀°Y₀°, X₀°Y₄₅°, and X₀°Y₄₅°. Dimensional accuracy, surface roughness, and part strength were measured by using digital vernier calliper, universal testing machine, and portable surface roughness tester, respectively. The results show that part orientation influences printed part quality, especially in accuracy and surface roughness. No part orientation studied delivered all positive quality expected, but overall, X₀°Y₀° orientation resulted the highest quality in terms of dimensional accuracy, mechanical properties, and cost.

1. Introduction
The first applications of three dimensional (3D) printing or additive manufacturing (AM) were in the area of rapid prototyping, which started as a fundamental procedure to construct prototype models. Rapid prototyping with 3D printing offers the adaptability essential to make this vital experimentation procedure conceivable for physical items and products. Among all of the additive manufacturing technologies, FDM is the standout amongst the regularly used technologies for manufacturing or engineering purposes. FDM is applicable for an assortment of thermoplastics resins and the process is low-cost when contrasted with other AM processes. Besides, the support material is less demanding to break away from the completed part. FDM part is perfect for shape, impeccable for fit and function testing since it can endure testing thoroughly without twisting, contracting or dampness assimilation [1].

For products with non-complex features, it is normally the best approach to emphasise on the commercial value. Targeting at orientation with the most minimal amount of deposited layers allows rising for at least two significant part parameters, with high opportunity to increase accuracy and occasionally surface quality. A final product made utilising FDM can be described by certain quantities, which are subjected to many conditions. Creating a precise and dimensionally stable part have always been a challenging goal of FDM technology. In the past, the effect of manufacturing build parameters
on a single objective of 3D printed part has been broadly investigated by different theoretical and experimental methods. Raut et al. [2] prepared and fabricated ASTM standard specimens in three geometrical axes with various part orientations to perform the tensile and flexural tests. They perceived that high tensile strength FDM parts with low manufacturing cost would occur at the built up orientation of y-axis of 0°; whereas FDM parts with good flexural strength and moderate fabrication cost would take place at built up orientation of x-axis of 0°. Afrose et al. [3] studied the fatigue characteristics of FDM printed part with polylactic acid (PLA) material by deliberating the impact of various build orientations for which the samples were manufactured in ASTM D638 standard. As reported by Górski et al. [4, 5], there are two main reasons for the effect of part orientation on mechanical characteristics. The first reason is the layers in between the FDM parts appear in weak bond, which leads to the strength properties to drop. The second cause is the FDM models which consistently show volume error within.

The issue of dimensional stability has become significant when components are proposed for assembly and customised utilisation. Tak et al. [6] studied the shrinkage degrees on the produced models by examining the effect of 3D printing setting on dimensional accuracy. They found that the decrease in size rises the level of shrinkage where the geometric forms directly influence on the deviations of the measurement. Nizam et al [7] studied on dimensional accuracy by using FDM technology to manufacture a sample with four general features of parts in various magnitudes. The authors observed and declared that FDM machine they were using was having low precision, especially in fabricating a part with rounded figure as the most of them exceed the device’s tolerance. Górski et al [8] utilised part orientation as the primary parameter of the FDM technology and determined the relationship with dimensional accuracy and repeatability of acquired products. They concluded that deviations are comparatively fewer for greater scales which implied that the bigger the body dimension, the more accurately it will be produced. Singh et al [9] found that the effect of parts placement on accuracy and mechanical properties has noticeable change when advancing along Y axis from the origin but not the extent in the X direction. The authors observed that there is a little abatement in mechanical properties and a small increment in dimensional accuracy error when progress along Y axis in the build. The slicing layer produced and the orientation at which the part is fabricated can directly affect the surface quality of the printed model. Badola and Vaishya [10] have conducted an experimental study and presented a couple of more parameters which could be adopted to manage the surface finish of a part, for example, build style, build envelope’s temperature as well as multi-contouring. Stair case effect is inevitable because of the nature of layer manufacturing process. It is usually established on inclined planes and rounded surface, resulting in a high value of surface roughness of the part. This effect is difficult to eliminate, but it can be reduced to some extent and thus increase the surface quality. Sreedhar et al. [11] reported that due to some layers of the FDM sample involve void material, the boundaries of the lateral part could not acquire sufficient tool movement. However, they stated that the issue could be prevented by increasing the amount of travel of the contour tool in those layers and limiting the raster route to assure the value of surface roughness is reducing. The research of Bakar et al. [12] indicated that contour width and internal raster could help in the bonding substance amongst layers and result in an improved surface quality. Vijay et al. [13] performed fractional factorial design in two stages for layer thickness and three tiers for orientation aspect to evaluate the ideal surface quality of the printed part.

From previous studies, it can be summarised that most of the investigations were centred on one particular build goal or a few build objectives regarding only one process variable, for example, the part orientation. In the present work, the characteristics and the effect of build orientation are examined on several build goals, including dimensional accuracy, part strength, building time, build material, support material, manufacturing cost, and surface quality of the 3D printed part. This investigation is performed based on the subsequent methodology, in which first step is to design and create 3D model. The second step is to transfer the designed model to 3D printer and print the parts with five different orientations (X0°Y0°, X90°Y0°, X0°Y90°, X90°Y45°, and X90°Y45°). The third step is to measure and average the results of dimensional accuracy, mechanical strength and surface roughness. The last step is to analyse the experiment results and identify the relationship between accuracy, strength and surface roughness with part orientation.
2. Materials and methods

The experimental test target was designed using Solidworks software and printed as shown in figure1. The specimen used is a bracket which was chosen because it contains many of the geometrical dimensioning and tolerance features. The experiment specimens were set to be five test prints which each of the five printed specimens applied its particular unique set of printed variables with changing part orientation. For the result authentication, the experiment was repeated thrice and therefore in total there are 15 samples. The models are produced by using the STRATASYS FDM machine (MOJO) default parameters setting and the other parameters, which are shown in table 1. Post-processing was needed to remove the support material. The model material required for each part, the support material required for each part as well as the build time were estimated by Control Panel software as shown in table 2.

### Table 1. FDM Process Parameters

| No. | Feature  | Dimension | Value (mm) |
|-----|----------|-----------|------------|
| 1   | Hole 1   | Diameter  | 5.71       |
| 2   | Hole 2   | Diameter  | 6.71       |
| 3   | Hole 3   | Diameter  | 8.23       |
| 4   | Cylinder | Thickness | 6.10       |

### Table 2. Properties for various orientation

| Sample No. | Orientation | Building Time (hr:min) | Model Material (cm³) | Support Material (cm³) |
|------------|-------------|------------------------|-----------------------|------------------------|
| 1          | X0°Y0°      | 4:15                   | 28.3                  | 14.5                   |
| 2          | X90°Y0°     | 4:50                   | 28.6                  | 16.9                   |
| 3          | X0°Y90°     | 7:23                   | 29.3                  | 29.6                   |
| 4          | X0°Y45°     | 6:25                   | 29.0                  | 25.8                   |
| 5          | X90°Y45°    | 5:54                   | 28.8                  | 20.1                   |

The data of building time, model material used and support material used can be obtained from the FDM machine log file. In the present case, adopted from Tagore et al. [14], the cost of each criterion and the estimated manufacturing cost for each orientation can be calculated by applying the formula in equation 1.

\[
\text{Total cost} = (\text{Machine hr. /min } \times \text{ Build up time}) + (\text{Model material } \times \text{ Model material cost}) + (\text{Support material } \times \text{ Support material cost})
\]

where
- Building hr cost = $10 / hr
- Model material cost = $0.2169 / cc
- Support material cost = $0.1735 / cc.

The measurement of dimensional accuracy was conducted by determining the dimensions of specimen features. Measurements were conducted via digital calliper with an accuracy of ±0.02 mm and the magnitudes were contrasted with the nominal dimensions (CAD model). The full analysis and investigation of dimensional accuracy were attained which showed in result segment. According to Chua et al [15], the tolerance in the x-axis is 0.127 mm.

\[
D(\%) = \left| \frac{A_{CAD} - A_{med}}{A_{CAD}} \right| \times 100\%
\]

(2)
where $A_{CAD}$ is the nominal size of CAD model set by the computer, $A_{mea}$ is the real size measured by a digital vernier calliper.

For determining the surface roughness of every specimen, a Mitutoyo Surf test SJ-301 portable surface tester is used. Depends on the size of the printed model, the contact needle of the surface tester can navigate to a range of 0.25 mm to 25 mm. Both surface roughness, Arithmetic Mean Deviation ($R_a$) and Average peak to valley height ($R_z$) was measured at four different positions. These quantities were applied in transversal path of the material surface for three times at each location of different part orientation.

Among mechanical strength tests, tensile test is the most common investigations to determine the material and part properties. Tensile tests were performed on the printed specimen three times for each part orientation where the experiment was carried out on an LR10KN Universal Materials Testing Machine. The force values were set to zero to neutralise any tensions produced in the equipment during part setting. This calibration secured an equivalent starting point over all the tests. The upper wedge grip of the machine shifted upward at a rate of 2 mm/min until the point when the test part broken. The stress and maximum fracture load were recorded continuously through Tinius Olsen software which associated with the analyser. Based on the parameters, the test times is extended to 2 to 5 minutes.

![Figure 1](image-url.png)

**Figure 1.** Specimen built at 1st orientation (X0° Y0°).

### 3. Results and discussion

As shown in table 3, orientation has significant influence on several main features such as the height of the part in the build direction. It determines the required manufacturing time and cost of final parts. The outcomes validate that specimen with a small degree have short building time. Besides, diminishing the contact region between the model and the support structure will reduce the building time and the cost as well. Therefore, based on the obtained results, the best option for the least manufacturing cost and fabricating time is sample 1 at the orientation of X0°Y0°.

| Sample No. (SN) | Building Time (hr:min) | Model Material (cc) | Support Material (cc) | Total Cost ($) |
|-----------------|------------------------|---------------------|-----------------------|---------------|
| 1               | 4:15                   | 28.3                | 14.5                  | 51.23         |
| 2               | 4:50                   | 28.6                | 16.9                  | 51.71         |
| 3               | 7:23                   | 29.3                | 29.6                  | 54.07         |
| 4               | 6:25                   | 29                  | 25.8                  | 53.35         |
| 5               | 5:54                   | 28.8                | 20.1                  | 52.31         |
Table 4. Dimensional accuracy of part features with different part orientation

| SN | Hole 1 Diameter (mm) |  |  |  | Deviation (mm) | Dimensional Accuracy (%) |
|----|----------------------|---|---|---|-----------------|------------------------|
|    | Measured Dimension   | Nominal Dimension | Avg |            |                 |                        |
|    | Test 1 | Test 2 | Test 3 |  |       |                        |
| 1  | 5.71   | 5.60   | 5.67   | 5.660 | -0.048 | 99.16                |
| 2  | 5.49   | 5.37   | 5.44   | 5.433 | -0.275 | 95.19                |
| 3  | 5.50   | 5.64   | 5.65   | 5.597 | -0.111 | 98.05                |
| 4  | 5.42   | 5.43   | 5.44   | 5.430 | -0.278 | 95.13                |
| 5  | 5.53   | 5.50   | 5.53   | 5.520 | -0.188 | 96.71                |

| SN | Hole 2 Diameter (mm) |  |  |  | Deviation (mm) | Dimensional Accuracy (%) |
|----|----------------------|---|---|---|-----------------|------------------------|
|    | Measured Dimension   | Nominal Dimension | Avg |            |                 |                        |
|    | Test 1 | Test 2 | Test 3 |  |       |                        |
| 1  | 6.68   | 6.73   | 6.64   | 6.683 | -0.025 | 99.63                |
| 2  | 6.52   | 6.48   | 6.47   | 6.490 | -0.218 | 96.75                |
| 3  | 6.51   | 6.68   | 6.60   | 6.597 | -0.111 | 98.34                |
| 4  | 6.57   | 6.63   | 6.53   | 6.577 | -0.131 | 98.04                |
| 5  | 6.57   | 6.47   | 6.53   | 6.523 | -0.185 | 97.25                |

| SN | Hole 3 Diameter (mm) |  |  |  | Deviation (mm) | Dimensional Accuracy (%) |
|----|----------------------|---|---|---|-----------------|------------------------|
|    | Measured Dimension   | Nominal Dimension | Avg |            |                 |                        |
|    | Test 1 | Test 2 | Test 3 |  |       |                        |
| 1  | 8.24   | 8.21   | 8.22   | 8.223 | -0.009 | 99.89                |
| 2  | 8.21   | 8.25   | 8.19   | 8.217 | -0.015 | 99.81                |
| 3  | 8.09   | 8.06   | 8.27   | 8.140 | -0.092 | 98.88                |
| 4  | 8.22   | 8.20   | 8.23   | 8.217 | -0.015 | 99.81                |
| 5  | 8.03   | 8.05   | 8.03   | 8.037 | -0.195 | 97.63                |

| SN | Cylinder Thickness (mm) |  |  |  | Deviation (mm) | Dimensional Accuracy (%) |
|----|-------------------------|---|---|---|-----------------|------------------------|
|    | Measured Dimension      | Nominal Dimension | Avg |            |                 |                        |
|    | Test 1 | Test 2 | Test 3 |  |       |                        |
| 1  | 6.26   | 6.27   | 6.31   | 6.280 | 0.180  | 97.05                |
| 2  | 6.13   | 6.18   | 6.17   | 6.160 | 0.060  | 99.02                |
| 3  | 6.23   | 6.22   | 6.24   | 6.230 | 0.130  | 97.87                |
| 4  | 6.31   | 6.30   | 6.35   | 6.320 | 0.220  | 96.39                |
| 5  | 6.20   | 6.19   | 6.18   | 6.190 | 0.090  | 98.52                |

From the results obtained in tables 5 and 6, it can be seen that all the three actual diameters of the hole presented negative deviation which is below their nominal values. As for the standard tolerance of the FDM device is ±0.127mm, the results showed that except for sample 1 and 3, the dimensional differences of holes for the other two samples are surpassing the range. While for the case of cylinder feature, all the measured values of the cylinder thickness are above the nominal dimension (positive deviation) and which some of them is beyond the standard tolerance except for samples 2 and 5.

Based on table 4, the accuracy of the hole is linearly increasing with the diameter of the hole. The most accurate of the hole is up to 99.89% which is sample 1, Hole 3 (Ø8.23mm) and the least is 95.13% at sample 4, Hole 1 (Ø5.71mm). The highest dimensional accuracy of the cylinder is 99.02% at sample 2 whereas the lowest is 96.39% at sample 4. Hence, it can be concluded that the best dimensional accuracy obtained for producing both hole and cylinder feature is at orientation X0°Y0°.

In general, the printed model displays a rougher surface because of the extrusion of unwinding semi-liquefied thermoplastic thin filament. Based on the table 5, the highest values of the surface roughness are recorded where the support materials are located.
Table 5. Surface roughness variation of each part orientation

| Location | Part 1 | Ra (um) | Rz (um) |
|----------|--------|---------|---------|
|          | Test 1 | Test 2 | Test 3 | Avg | Test 1 | Test 2 | Test 3 | Avg |
| 1        | 2.32   | 1.88   | 1.18   | 1.793 | 7.24 | 5.94   | 4.87   | 6.017 |
| 2        | 2.42   | 2.69   | 1.91   | 2.340 | 7.88 | 7.67   | 7.73   | 7.760 |
| 3        | 3.22   | 1.06   | 3.08   | 2.453 | 9.40 | 5.79   | 12.06  | 9.083 |
| 4        | 15.34  | 14.47  | 12.01  | 13.940 | 58.32 | 49.22 | 44.39 | 50.643 |

| Location | Part 2 | Ra (um) | Rz (um) |
|----------|--------|---------|---------|
|          | Test 1 | Test 2 | Test 3 | Avg | Test 1 | Test 2 | Test 3 | Avg |
| 1        | 6.51   | 6.60   | 4.80   | 5.970 | 31.09 | 34.33 | 27.27 | 30.897 |
| 2        | 5.77   | 9.55   | 8.06   | 7.793 | 34.76 | 42.46 | 38.54 | 38.587 |
| 3        | 10.17  | 13.04  | 10.34  | 11.183 | 58.34 | 51.58 | 51.65 | 53.857 |
| 4        | 1.84   | 0.81   | 1.89   | 1.513 | 5.09 | 3.55   | 5.94 | 4.860 |

| Location | Part 3 | Ra (um) | Rz (um) |
|----------|--------|---------|---------|
|          | Test 1 | Test 2 | Test 3 | Avg | Test 1 | Test 2 | Test 3 | Avg |
| 1        | 10.46  | 9.40   | 10.37  | 10.077 | 46.23 | 44.22 | 42.27 | 44.240 |
| 2        | 10.34  | 9.82   | 10.43  | 10.197 | 50.44 | 47.58 | 48.25 | 48.757 |
| 3        | 4.73   | 3.44   | 3.90   | 4.023 | 20.45 | 24.54 | 19.47 | 21.487 |
| 4        | 10.28  | 10.19  | 13.49  | 11.320 | 44.54 | 49.97 | 55.10 | 49.870 |

| Location | Part 4 | Ra (um) | Rz (um) |
|----------|--------|---------|---------|
|          | Test 1 | Test 2 | Test 3 | Avg | Test 1 | Test 2 | Test 3 | Avg |
| 1        | 12.57  | 11.18  | 11.92  | 11.890 | 48.87 | 47.35 | 49.75 | 48.657 |
| 2        | 12.54  | 10.94  | 11.43  | 11.637 | 53.26 | 52.95 | 57.35 | 54.520 |
| 3        | 5.05   | 5.61   | 4.26   | 4.973 | 19.58 | 18.71 | 18.05 | 18.780 |
| 4        | 14.25  | 13.89  | 14.98  | 14.373 | 61.35 | 59.53 | 61.89 | 60.923 |

| Location | Part 5 | Ra (um) | Rz (um) |
|----------|--------|---------|---------|
|          | Test 1 | Test 2 | Test 3 | Avg | Test 1 | Test 2 | Test 3 | Avg |
| 1        | 14.79  | 14.95  | 15.02  | 14.920 | 57.14 | 60.70 | 57.42 | 58.420 |
| 2        | 13.24  | 16.19  | 15.73  | 15.053 | 59.40 | 65.66 | 63.99 | 63.017 |
| 3        | 18.11  | 15.74  | 16.93  | 16.927 | 72.48 | 61.00 | 68.30 | 67.260 |
| 4        | 10.96  | 10.62  | 10.58  | 10.720 | 48.95 | 46.57 | 44.98 | 46.833 |

In FDM technologies, part orientation influences shape quality due to fabricating the component in rises in the Z-direction and also the routing of slicing. A fine surface finish is acquired from the areas of the part that is regularly smoothened by the extrusion nozzle which is not directly in contact with the support material and build platform. Hence, the low value of surface roughness will always achieve at the top facing surface of a 3D printed part [16]. The result indicated that sample 2 is having the lowest value of surface roughness (1.51µm) among all five parts. This is because for the other samples, there is a curved surface of the part which the part mass is upright on the support. Stair-stepping would occur, thus making a rough surface structure and giving out the large value of surface roughness. Moreover, for the specimen 2, there is not much load from the part weight on the contact area between the support material and the part or the part load is not falling in the support. Therefore, it can be concluded that the best surface quality obtained for producing a part is at orientation X90°Y0°.
A general experimental study was proposed to investigate the effects of part orientation on tensile strength and maximum fracture load of printed samples. Based on table 6, the orientation of X0°Y0° (sample 1) resulted in the largest values for tensile strength and load at fracture point, whereas X0°Y90° (sample 3) demonstrated the lowest values for both mechanical properties. For other samples, the amounts mainly fall in between that of 0° and 90° in the y-axis. This variance can be expounded by examining inter raster composite adhesions as well as trans-raster strength, which means the tensile force of each raster. In 0° orientation of the printed parts, the overshoot of inter-raster compound had minimal effect on the mechanical strength as every raster was moving upward of its longitudinal axis, instigating trans-raster tensile failure. However, for 90° orientation samples, the load was applied vertically to raster longitudinal axis which leads to weaker bonds. For this circumstance, layer bond alongside the shell number in the samples with 90° orientation directly influences the flexible capability, since the internal raster synthesis bonds amongst adjoining raster endured through the greater part of the exerted force.

Table 6. Experimental results for mechanical properties of different part orientation

| SN | Tensile Strength (MPa) | Maximum Fracture Load (N) |
|----|------------------------|---------------------------|
|    | Experimental Test 1    | Experimental Test 2        | Experimental Test 3 | Avg | Experimental Test 1 | Experimental Test 2 | Experimental Test 3 | Avg |
| 1  | 29.01                  | 29.98                     | 29.08               | 29.36 | 1392.25             | 1439.23             | 1395.78               | 1409.09 |
| 2  | 23.16                  | 24.02                     | 24.88               | 24.02 | 1111.55             | 1153.02             | 1194.15               | 1152.91 |
| 3  | 12.49                  | 16.22                     | 15.43               | 14.71 | 599.65              | 778.62              | 740.56               | 706.28  |
| 4  | 19.77                  | 17.49                     | 20.55               | 19.27 | 948.78              | 986.27              | 924.84               |         |
| 5  | 18.92                  | 23.11                     | 21.76               | 21.26 | 907.96              | 1004.50             | 1020.51               |         |

4. Conclusion
In this study, a 3D model was established to study the effects of the part orientation on dimensional accuracy, part strength, and surface quality. Results showed that X0°Y0° (sample 1) and X90°Y0° (sample 2) would be the most appropriate part orientation to produce the part with the highest dimensional accuracy and good surface quality, respectively. Orientation X0°Y0° demonstrated the highest values for tensile strength and maximum fracture load, giving 29.36 MPa and 1409.09 N, respectively. To fabricate a model with the least manufacturing cost, part orientation X0°Y0° would be the best choice.

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