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Investigation of the effects of fused deposition modeling process parameters on the dimensional accuracy of PLA+ using the Taguchi method

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Abstract

Dimensional accuracy is a crucial aspect of Fused Deposition Modeling (FDM) based Three-Dimensional (3D) printing, as deviations from the intended dimensions may lead to product malfunction and difficulties in component assembly. Various process parameters generally contribute to such inaccuracies in 3D printing. This study aims to evaluate the effects of four main FDM parameters-layer height, infill density, print speed, and nozzle temperature- on the dimensional accuracy of printed parts using Polylactic Acid (PLA+) material. The primary focus of this research is to enhance dimensional accuracy. To achieve this objective, a Taguchi experimental design was employed, providing a structured and efficient approach to optimizing process parameters while minimizing the number of experiments. An L27 orthogonal array matrix was selected to analyze the influence of parameters at three levels. Based on the analysis of Signal-to-Noise (S/N) ratios and response data, the optimal parameter combination was identified as follows: layer height of 0.1 mm, infill density of 100%, print speed of 40 mm/s, and nozzle temperature of 210°C. Confirmation tests with these settings demonstrated an improvement in dimensional accuracy, as indicated by average dimensional deviations of 0.27 mm (X-axis), 0.08 mm (Y-axis), and 0.08 mm (Z-axis) from the nominal in dimensional accuracy, with average measurements of 11.73 mm on the X-axis, 7.08 mm on the Y-axis, and 21.08 mm on the Z-axis. These results confirm that the selected parameter configuration ensures dimensional stability and consistency.

Keywords:
3D Printing, dimension, accuracy, PLA+

1 Introduction

Additive manufacturing technology, particularly Three-Dimensional (3D) printing using the Fused Deposition Modeling (FDM) method, has become a key component in the advancement of modern manufacturing industries [1]. The popularity of this technology continues to grow due to its ability to rapidly produce prototypes and fabricate functional components at relatively low cost [2]. Despite its rapid growth and widespread adoption, dimensional accuracy in printed parts remains a major challenge that hinders optimal utilization of FDM technology [3]. Dimensional inaccuracies may affect component functionality, lead to errors during assembly, and ultimately reduce overall product quality [4]. Therefore, an in-depth investigation of the factors influencing dimensional accuracy is essential [5].

Dimensional deviations in 3D-printed products can adversely affect functional performance, complicate assembly, and reduce overall quality standards [6]. Several process parameters, such as nozzle temperature, infill density, print speed, and layer height, significantly influence dimensional accuracy [7]. Proper control and optimization of these parameters are therefore essential. Adjusting the nozzle temperature appropriately can prevent issues such as stringing and under-extrusion, while regular nozzle cleaning helps avoid clogging caused by material buildup [9]. Moreover, selecting the appropriate nozzle temperature is critical to the quality of the printed output [10]. Although such practices are commonly employed, a systematic scientific method for determining the optimal combination of process parameters when using Polylactic Acid (PLA+) in FDM printing is still lacking [11]. Consequently, previous studies have aimed to improve dimensional accuracy by identifying and optimizing process parameters that significantly affect printing precision [12]. Some of these studies employed the Taguchi method, a well-established statistical approach known for its efficiency in process optimization, to determine the optimal parameter configuration to enhance dimensional accuracy [13].

The Taguchi method provides a systematic approach to analyzing and optimizing process parameters [14]. This method is designed to improve product quality by minimizing variation and identifying the variables that most significantly influence the outcome [15]. In this study, the variables expected to affect the dimensional accuracy of 3D-printed parts using PLA+ include extruder temperature (typically 190-250°C), printing speed (approximately 60 mm/s), and layer height (0.2 mm) [16]. Previous studies have shown that changes in these parameters can directly impact the dimensional quality of the printed product [17]. Therefore, further analysis is required to determine the optimal parameter combination to achieve high-dimensional accuracy [18].

In previous studies, optimization of 3D printing process parameters was conducted using the Taguchi method with an L_{27} orthogonal array [19]. The parameters evaluated were nozzle temperature, layer height, print speed, infill percentage, and heated bed temperature [20]. The results indicated that the optimal parameter configuration for achieving dimensional accuracy in the specimen's outer diameter was a nozzle temperature of 190°C, a layer height of 0.15 mm, a print speed of 45 mm/s, 12% infill, and a bed temperature of 45°C, yielding a measured diameter of 29.98 mm. For specimen height, the optimal combination consisted of a nozzle temperature of 185°C, a layer height of 0.20 mm, a print speed of 40 mm/s, 8% infill, and a bed temperature of 40°C, yielding a height of 39.85 mm [21]. The most effective parameter set for optimizing both dimensions (outer diameter and specimen height) was found to be a nozzle temperature of 185°C, a layer height of 0.20 mm, a print speed of 40 mm/s,12% infill, and a bed temperature of 40°C, yielding a measurement of 34.87 mm [22]. These findings highlight that the proper selection of process parameters is crucial for improving dimensional accuracy in FDM-printed products [23].

In previous studies, the process parameters examined included nozzle temperature, bed temperature, flow rate, print speed, layer thickness, infill overlap percentage, infill density, and infill speed [24]. Based on the experimental results, the highest specimen height was achieved using an infill density of 90%, print speed of 20 mm/s, layer height of 0.2 mm, and nozzle temperature of 200°C, as well as an infill density of 95%, print speed of 20 mm/s, layer height of 0.2 mm, and nozzle temperature of 210°C, each with a value of 19.99 mm. In comparison, the lowest value was obtained with an infill density of 100%, a print speed of 40 mm/s, a layer height of 0.2 mm, and a nozzle temperature of 190°C, yielding a height of 19.73 mm [25]. Further analysis showed that the parameters with the most significant influence on specimen height, in descending order, were nozzle temperature (235°C), bed temperature (100°C), infill density (25%), infill overlap (10%), layer thickness (0.30 mm), print speed (40 mm/s), infill speed (40 mm/s), and flow rate (90%) [26].

Based on research findings on the accuracy of 3D-printed gears, the optimal layer thickness range for gear fabrication is 0.1-0.2 mm [27]. This range does not exceed half of the standard nozzle diameter of 0.4 mm, thereby enabling a smoother, more controlled raster pattern and improved dimensional accuracy. Additionally, the recommended print speed for ABS filament ranges from 30 mm/s to 50 mm/s, as this range can produce stable raster structures, thereby ensuring dimensional precision in the printed object [28]. The recommended infill density for gear components ranges from 20% to 40% to balance mechanical strength and material efficiency [29]. Experimental results indicate that the most optimal printing configuration consists of a 0.15 mm layer thickness, a 20% gyroid infill pattern, and a print speed of 30 mm/s [30]. Furthermore, load-simulation results indicate that the printed gear can withstand a maximum load of 85 kg [31]. To achieve good impact strength, a 100% infill density with Tough PLA filament is recommended, combined with optimization of other process parameters to enhance the specimen's dimensional accuracy [32].

Based on previous studies and the research conducted in this work, the present study focuses on investigating the influence of FDM process parameters, including layer height, infill density, printing speed, and nozzle temperature, on the dimensional accuracy of printed products made from PLA+. By employing the Taguchi method with an L27 orthogonal array, this study aims to determine the optimal parameter combination to achieve improved dimensional accuracy while maintaining consistent printed results.

2 Research methodology

This study used a CoreXY 3D printer manufactured by Shenzhen Creality 3D Technology, Jin Cheng Yuan, China. The machine was used to print the research specimens. The 3D printer functions to fabricate the test specimens. The detailed technical specifications of the CoreXY 3D printing machine [33] can be found in Table 1.

Table 1. Machine specifications

Parameters	Value
Model number	CoreXY 3D printer
Build size	220 × 220 × 250 mm
Machine size	± 400 × 400 × 500 mm
Rated power	270 Watt
Rated voltage	AC115/230V
Rated current	4A / 2.1A

The PLA+ Filament, manufactured by Shenzhen eSUN Industrial Co., Ltd., was used to produce the samples. A bolt-shaped specimen was selected in this study because it is a commonly used functional component in mechanical assemblies and enables evaluation of dimensional accuracy across multiple geometric features, including diameter, height, and thread consistency. Although simpler geometries may facilitate basic dimensional measurement, the bolt geometry provides a more realistic assessment of dimensional deviations encountered in practical FDM applications. The manufacturer-recommended specifications for PLA+ filament are presented in Table 2.

Table 2. Specifications of filament

Filament	1.75 mm
Print temperature	190° - 220°
Print bed temperature	50°C- 80°C
Roundness tolerance	0.01-0.05
Nett weight	1 Kg/roll
Infill speed	30 mm/s- 60 mm/s

2.1 Specimen

This study employed both experimental and simulation methods using a factorial model approach. This approach was selected for its effectiveness in identifying relationships between various 3D printing parameters and the dimensional accuracy of the resulting specimens. Fig. 1 shows the standard dimensions of the test specimen used to evaluate dimensional accuracy. The dimensional verification of the specimens was performed using a Mitutoyo caliper with a precision of 0.02 mm and a measurement range of up to 150 mm.

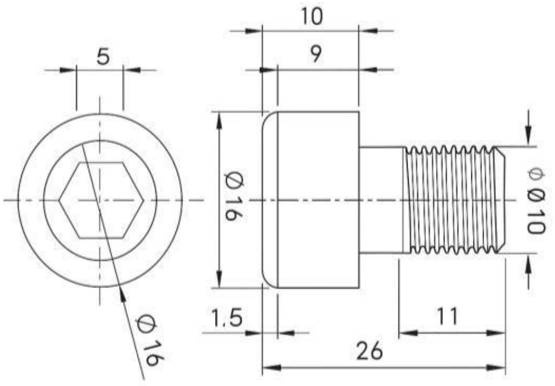


Fig. 1. Specimen design

2.2 Specimen dimension measurement

Fig. 2 illustrates the specimen positioned within a 3D Cartesian coordinate system (X, Y, Z) in a cavalier projection. The Z-axis is oriented vertically upward, the X-axis is horizontal, and the Y-axis forms a 45° angle with the X-axis. This orientation facilitates measurement of the outer diameter, inner diameter, and specimen height, while also providing a clear view of the thread details and geometric features, thereby enabling more accurate measurement and analysis.

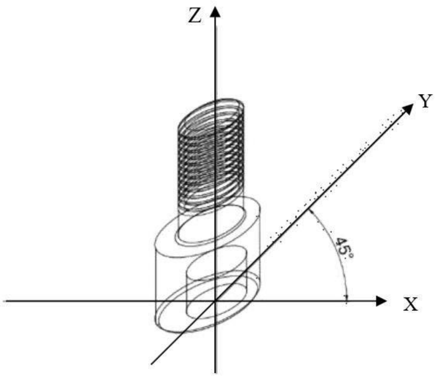


Fig. 2. Specimen dimension measurement

In Table 3, the selected process parameters: layer height, infill density, print speed, and nozzle temperature were chosen based on their significant influence on dimensional accuracy as reported in previous studies and manufacturer recommendations for PLA+ filament. The levels for each factor were selected to represent low, medium, and high settings commonly used in practical FDM printing, thereby enabling a comprehensive evaluation of parameter effects while maintaining process stability. To evaluate the impact of process parameter combinations in 3D printing on specimen dimensional accuracy, the first step is to define the parameters to be used.

Table 3. Process parameters of the study

Factor	Process parameters	Levels		
		1	2	3
1	Infill density (%)	90	95	100
2	Print speed (mm/s)	20	30	40
3	Layer height (mm)	0.1	0.2	0.3
4	Nozzle temperature	190	200	210

The analysis of the degrees of freedom calculation shows that the minimum required value is 6; therefore, the selection of the orthogonal matrix must meet this criterion (Table 4). In this study, the orthogonal matrix L_{27} (3^4), consisting of 4 columns and 27 rows, was employed. Each column represents the factors being studied, while the rows indicate the possible combinations of treatment levels. The use of this orthogonal matrix was chosen because it accommodates factor variations in a balanced manner, minimizes bias in data collection, and enhances the reliability of the results in experimental design. The Taguchi characteristic used in this study is nominal, as the purpose of the experiment is to obtain test results as close as possible to the target value with minimal variation.

Performance is considered optimal when the response is precisely at the expected value, thereby yielding results that are more consistent, stable, and aligned with quality standards.

Table 4. Factorial design of the study using orthogonal array L_{27}

Exp.	Infill density (%)	Print speed (mm/s)	Layer height (mm)	Nozzle temperature (°C)
1	90	20	0.1	190
2	90	20	0.1	190
3	90	20	0.1	190
4	90	20	0.2	200
5	90	30	0.2	200
6	90	30	0.2	200
7	90	40	0.3	210
8	90	40	0.3	210
9	90	40	0.3	210
10	95	20	0.2	210
11	95	20	0.2	210
12	95	20	0.2	210
13	95	30	0.3	190
14	95	30	0.3	190
15	95	30	0.3	190
16	95	40	0.1	200
17	95	40	0.1	200
18	100	40	0.1	200
19	100	20	0.3	200
20	100	20	0.3	200
21	100	20	0.3	200
22	100	30	0.1	210
23	100	30	0.1	210
24	100	30	0.1	210
25	100	40	0.2	190
26	100	40	0.2	190
27	100	40	0.2	190

2.3 Printing process

The specimens for dimensional accuracy testing were printed in 81 experimental runs, with each parameter set printed three times. Fig. 3 illustrates the specimen printing process.

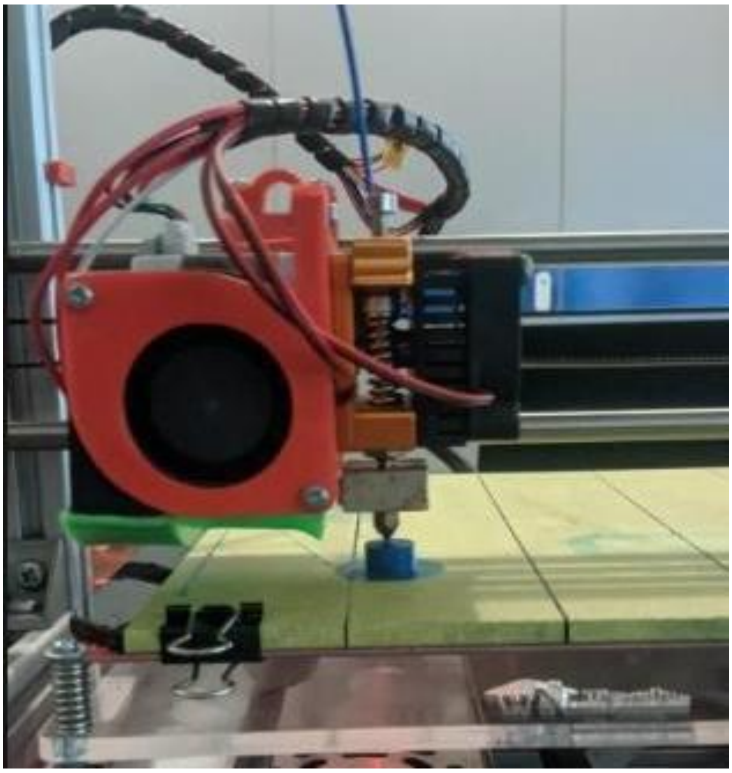


Fig. 3. Specimen printing process

2.4 Specimen printing results

Fig. 4 shows a series of 3D-printed specimens arranged systematically by research group or variable. This arrangement aims to facilitate the identification and comparison between specimens. Fig. 5 shows an example of a 3D-printed bolt-shaped specimen. This specimen is used as a test object to evaluate print quality and conformity to the original design.

Fig. 4. All specimens

Fig. 5. Specimens

3 Results and discussion

This section presents the results of specimen fabrication using a CoreXY 3D printer, along with an analysis of the experimental data. The discussion evaluates dimensional accuracy by comparing printed specimens with nominal CAD dimensions, measured along the X, Y, and Z axes, to assess the influence of printing parameters on specimen quality and precision.

3.1 Specimen measurement

The specimen measurement was performed using a digital caliper along three principal axes: X, Y, and Z (Fig. 6 to Fig. 8). The X-axis measurement was used to determine the specimen's width, while the Y-axis measurement was used to obtain height data. Meanwhile, the Z-axis measurement was performed to determine the specimen's length. The measurement data were then used as a reference for dimensional analysis and as the basis for assessing the specimen's conformity to the predetermined design standards.

Fig. 6. Specimen measurement on the X

Fig. 7. Specimen measurement on the Y

Fig. 8. Specimen measurement on the Z

3.2 Specimen measurement results

The data presented represent the test results of the specimens at each measurement point. The value at each point was obtained by dividing the initial measurement result in half. Subsequently, to determine the final value for each replication, the average of the three measurement points was calculated. The measurement results can be seen in Table 5

Table 5. Measurement results

EXP	X1	X2	X3	X Avg	X Dev	Y1	Y2	Y3	Y Avg	Y Dev	Z1	Z2	Z3	Z Avg	Z Dev
1	12.01	12.01	11.09	11.703	0.435	7.01	7.01	7.01	7.10	0.000	21.07	21.08	21.08	21.070	0.058
2	11.06	11.13	11.18	11.120	0.006	6.41	6.12	6.18	6.24	0.012	20.75	21.13	20.98	20.953	0.193
3	11.04	11.01	11.05	11.030	0.002	6.14	6.10	6.26	6.17	0.007	20.84	20.78	20.94	20.853	0.081
4	12.00	12.01	12.01	12.007	0.006	6.01	6.01	7.02	6.34	0.584	21.04	21.05	21.06	21.050	0.010
5	12.01	12.02	12.02	12.017	0.006	5.09	7.02	6.00	6.037	0.971	22.00	21.19	21.19	21.460	0.469
6	11.09	12.00	11.08	11.390	0.521	7.01	6.01	7.03	6.683	0.583	21.07	21.06	21.07	21.067	0.006
7	12.00	12.00	12.01	12.003	0.006	6.01	5.09	6.03	5.710	0.520	21.08	21.08	22.00	21.387	0.531
8	12.00	12.00	12.00	12.000	0.000	6.03	6.01	7.02	6.353	0.584	21.09	22.00	22.01	21.700	0.517
9	12.01	12.00	12.01	12.007	0.006	6.01	6.00	6.01	6.007	0.006	21.06	21.06	21.06	21.060	0.000
10	11.09	11.08	12.01	11.393	0.516	7.00	7.01	7.02	7.010	0.010	21.09	21.08	22.00	21.390	0.519
11	11.09	12.01	12.00	11.700	0.522	7.03	7.02	7.04	7.030	0.010	21.09	22.00	22.00	21.697	0.522
12	12.04	12.00	12.01	12.017	0.522	7.03	7.02	7.00	7.017	0.015	21.08	21.08	21.08	21.080	0.000
13	11.17	10.98	10.91	11.020	0.013	6.06	6.26	6.21	6.180	0.080	20.95	20.86	20.94	20.917	0.049
14	11.06	10.94	10.90	10.970	0.007	6.23	5.95	6.37	6.180	0.017	20.94	20.84	20.77	20.850	0.087
15	10.94	11.12	10.90	10.990	0.010	5.90	6.36	6.30	6.190	0.019	20.84	20.82	20.78	20.813	0.030
16	12.01	12.01	12.00	12.007	0.006	6.00	6.01	7.02	6.343	0.588	21.07	21.06	21.06	21.063	0.006
17	12.01	12.00	12.00	12.003	0.006	6.00	7.00	7.03	6.677	0.588	21.09	21.08	21.09	21.087	0.006
18	12.01	12.00	12.00	12.003	0.006	6.03	6.09	6.06	6.060	0.030	21.09	21.08	21.09	21.087	0.006
19	12.01	12.03	12.01	12.017	0.012	6.01	7.03	7.04	6.693	0.598	21.07	21.08	22.01	21.387	0.541
20	12.00	12.00	12.01	12.003	0.006	6.00	7.02	6.01	6.343	0.588	21.06	21.07	21.06	21.063	0.006
21	11.08	12.00	12.01	11.697	0.518	6.02	7.01	7.01	6.680	0.570	21.09	21.08	21.08	21.083	0.006
22	12.01	12.01	12.02	12.013	0.006	7.01	6.00	7.01	6.673	0.577	21.07	21.06	21.08	21.063	0.038
23	12.02	12.01	12.01	12.013	0.006	7.02	7.02	7.01	7.017	0.006	21.06	21.08	22.00	21.053	0.519
24	12.01	12.02	12.00	12.01	0.010	7.00	7.02	7.00	7.007	0.012	21.09	21.08	21.08	21.083	0.006
25	11.22	10.95	11.21	11.13	0.016	6.30	6.31	6.12	6.240	0.009	21.05	21.23	21.02	21.100	0.114
26	11.34	11.10	11.09	11.17	0.014	6.21	6.26	6.29	6.253	0.003	20.69	20.78	20.57	20.680	0.107
27	11.10	11.11	11.12	11.10	0.001	6.16	6.20	6.18	6.180	0.002	20.78	20.77	20.94	20.830	0.98

3.3 Graph of measurement results

The diagram in Fig. 9 illustrates the average X-axis measurements from 27 samples, ranging from 11.97 to 12.01 mm, which is close to the reference dimension of 12 mm. Several samples, including numbers 2, 3, 13–15, and 25–27, exhibited lower values, with the weakest below 11.20 mm. The most significant deviation from the reference size was 0.02 mm, whereas the smallest was 0.00 mm. Overall, the measurement results were reasonably consistent, although slight fluctuations were observed due to variations in parameters and testing conditions. In contrast to the study by C. Malinda et al., which employed five process parameters, the present study achieved improved dimensional accuracy along the X-axis by using only four parameters [5].

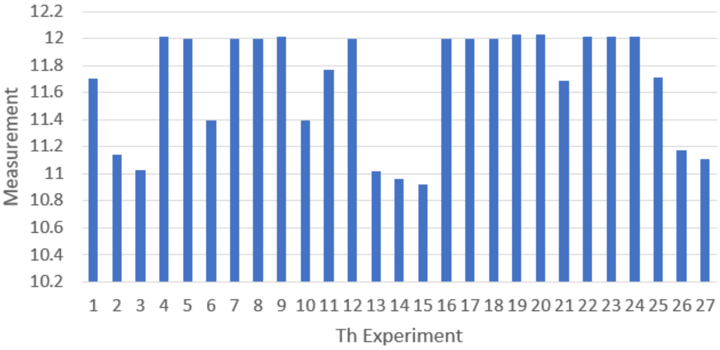


Fig. 9. X-axis diagram

The diagram in Fig. 10 presents the average Y-axis measurements from 27 samples, ranging from 6.58 to 7.07 mm. Most of the data fall within the range of 6.20–6.80 mm, while samples 1, 10, 12, and 23 are close to 7.00 mm, and samples 7 and 9 are below 6.00 mm. The most significant deviation from the 7 mm reference dimension was 0.41 mm, whereas the smallest was 0.007 mm. These results indicate that the measurements were generally consistent, despite minor variations among samples. These findings demonstrate a clear improvement over previous studies that reported only dimensional accuracy percentages without performing direct measurements along all three axes (X, Y, and Z). Consequently, the results of this study can serve as a more reliable and precise reference for dimensional accuracy evaluation [3], [8], [17].

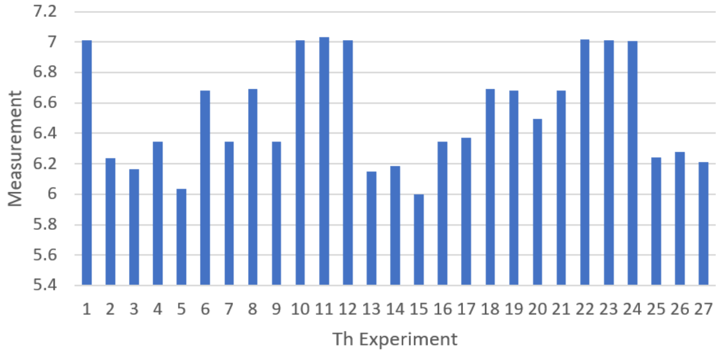


Fig. 10. Y-axis diagram

The diagram in Fig. 11 shows the average Z-axis measurements from 27 samples, ranging from 20.97 to 21.36 mm. Most of the data fall within the 21.0–21.2 mm range, with samples 8 and 11 approaching 21.7 mm, while samples 14, 15, and 26 are around 20.6 mm. The most significant deviation from the nominal size of 21 mm is 0.36 mm, and the smallest is 0.02 mm. This confirms that the Z-axis measurement results are relatively stable despite inter-sample variability. Consistent with the discussion of the Y-axis measurement results, the Z-axis measurements also yield more detailed outcomes than previous studies on dimensional accuracy that employed only four process parameters [3], [8], [17], [21].

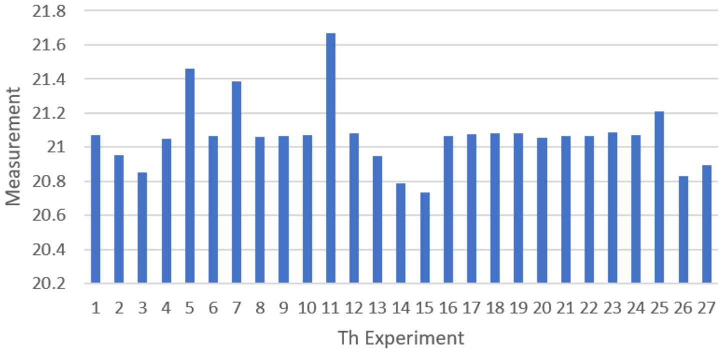


Fig. 11. Z-axis diagram

3.4 Table analysis on the X-axis

The processed data were visualized in Fig. 12, which indicates the optimal parameter combination: nozzle temperature 200°C, layer height 0.2 mm, print speed 40 mm/s, and infill density 100%. The optimal parameters obtained in this study represent a refinement of previous research that identified optimal process settings for studies of the dimensional accuracy of 3D-printed products, with measurements along the X, Y, and Z axes. These parameters include nozzle temperature [6], layer height [12], print speed [15], and infill density [19].

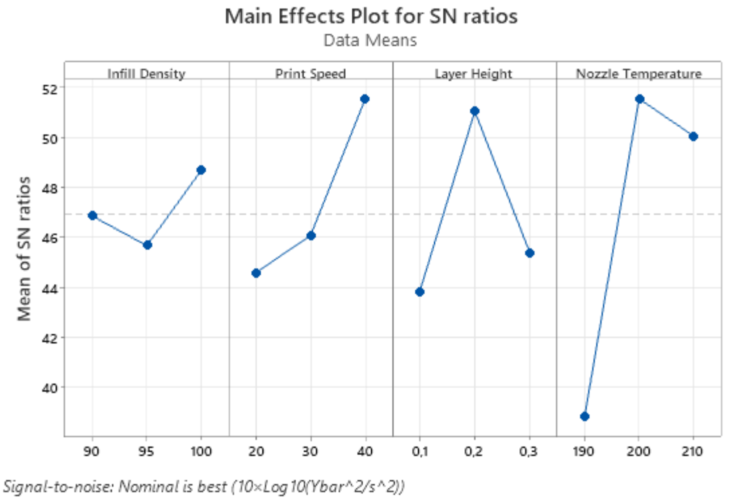
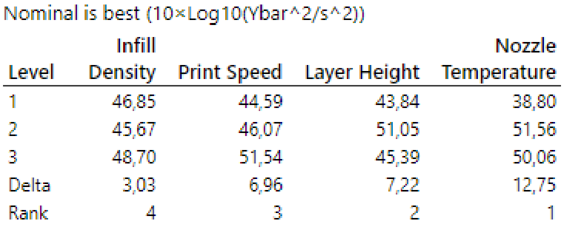


Fig. 12. X-axis

Based on the analysis shown in Table 6, the process factors with the most significant influence on dimensional accuracy along the X-axis, in order, are nozzle temperature, layer height, print speed, and infill density. These results demonstrate that nozzle temperature plays a critical role in improving the dimensional accuracy of printed products, which is consistent with findings reported in previous studies [12], [18], [19].

Table 6. Signal-to-Noise (S/N) ratio of the X-axis



Nominal is best (10×Log10(Ybar^2/s^2))

Level	Infill Density	Print Speed	Layer Height	Nozzle Temperature
1	46,85	44,59	43,84	38,80
2	45,67	46,07	51,05	51,56
3	48,70	51,54	45,39	50,06
Delta	3,03	6,96	7,22	12,75
Rank	4	3	2	1

Fig. 13 presents the interaction plot for the X-axis, showing that increasing infill density and nozzle temperature tend to improve the SN ratio. Meanwhile, a layer height of 0.2 mm provides the most stable results compared to 0.1 mm and 0.3 mm. A higher nozzle temperature, particularly 210°C, consistently yields higher-quality results. The combination of 100% infill, 0.2 mm layer height, and a nozzle temperature of 210°C yields optimal performance. This indicates the presence of significant interactions among the factors in influencing the quality of 3D prints.

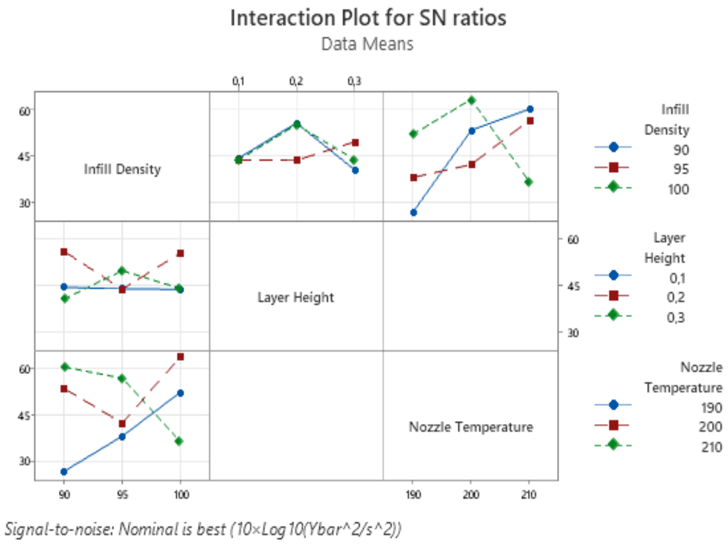


Fig. 13. Interaction plot of the X-axis

The interactions among process parameters were determined to evaluate the individual and combined effects of the tested parameters, as indicated by previous studies involving multiple process variables, particularly with respect to dimensional accuracy responses [13], [22], [23]. These interactions are critical for defining the characteristics of each specimen and for evaluating resulting responses, such as impact strength, tensile strength, and surface roughness [9], [11], [14], [19], [25].

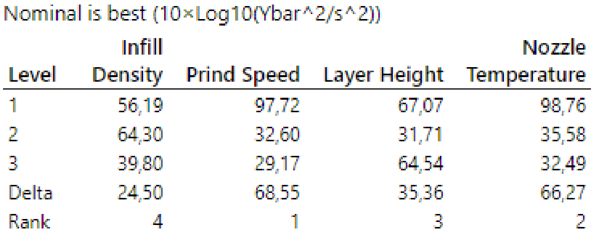
3.5 Table analysis on the Y-axis

Based on the data shown in Fig. 14, the optimal parameter combination was achieved at a nozzle temperature of 190 °C, a layer height of 0.1 mm, a print speed of 20 mm/s, and an infill density of 95%. Based on the analysis shown in Table 7, the process factors with the most significant influence on dimensional accuracy along the Y-axis, in order, are print speed, infill density, layer height, and nozzle temperature.

Fig. 14. Y-axis

The results of this study indicate that print speed significantly improves the dimensional accuracy of 3D-printed products, particularly along the Y-axis, consistent with findings reported in previous studies [28]. Fig. 15 shows that a print speed of 20 mm/s and a nozzle temperature of 190°C produced the highest SN ratio, while variations in infill density had little effect. The optimal combination was observed at 95–100% infill, with print speed and nozzle temperature as the dominant factors.

Table 7. S/N Ratio of Y-Axis



Nominal is best (10×Log10(Ybar^2/s^2))

Level	Infill Density	Prind Speed	Layer Height	Nozzle Temperature
1	56,19	97,72	67,07	98,76
2	64,30	32,60	31,71	35,58
3	39,80	29,17	64,54	32,49
Delta	24,50	68,55	35,36	66,27
Rank	4	1	3	2

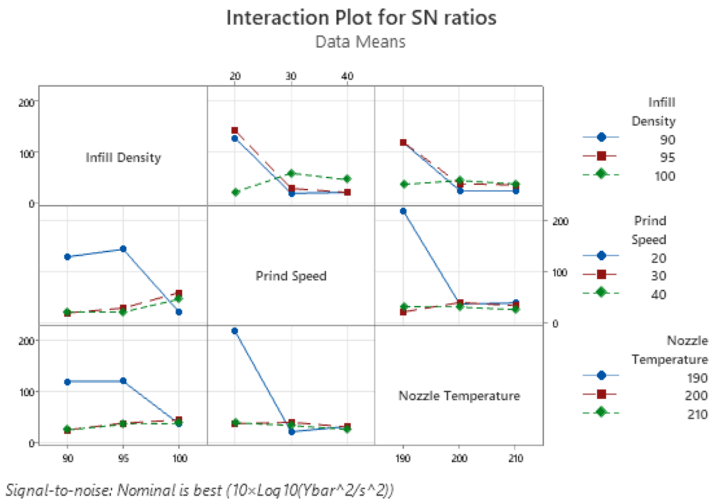


Fig. 15. Interaction plot of the Y-axis

3.6 Table analysis on the Z-axis

Fig. 16 shows that the optimal parameter combination was achieved at an infill density of 95%, a print speed of 30 mm/s, a layer height of 0.1 mm, and a nozzle temperature of 190 °C.

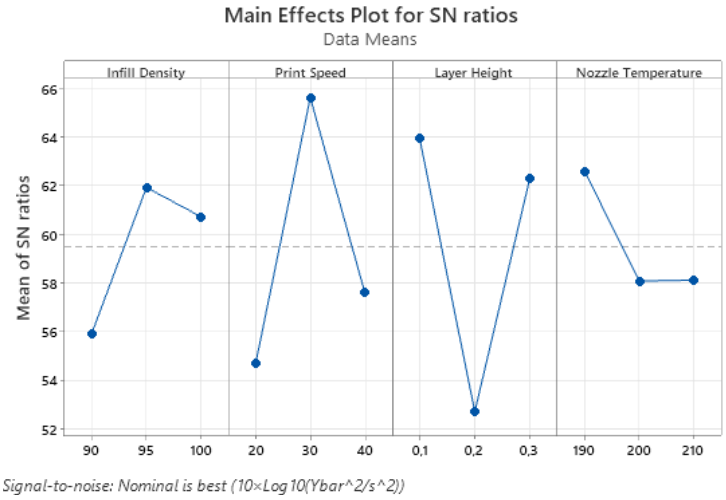
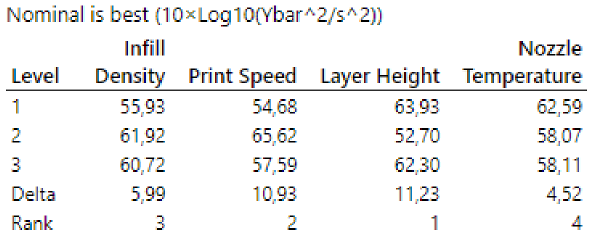


Fig. 16. Z-Axis

Based on the analysis shown in Table 8, the process factors with the most significant influence on dimensional accuracy along the Z-axis, in order, are layer height, print speed, infill density, and nozzle temperature. In this study, the results demonstrate that, for dimensional accuracy in the Z-axis orientation, the layer height parameter has a dominant influence, in agreement with observations reported in previous studies [6], [12], [17].

Table 8. S/N Ratio of Z-Axis


Nominal is best (10×Log10(Ybar^2/s^2))

Level	Infill Density	Print Speed	Layer Height	Nozzle Temperature
1	55,93	54,68	63,93	62,59
2	61,92	65,62	52,70	58,07
3	60,72	57,59	62,30	58,11
Delta	5,99	10,93	11,23	4,52
Rank	3	2	1	4

The graph in Fig. 17 shows that an infill of 95–100%, a print speed of 30 mm/s, a layer height of 0.2 mm, and a nozzle temperature of 210 °C produce the best SN ratio. The factors most influencing print quality are print speed and nozzle temperature, while infill and layer height have a lesser effect.

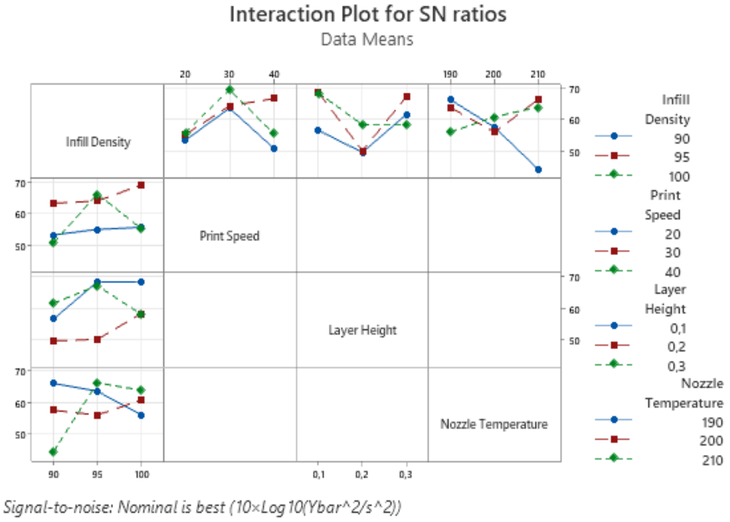


Fig. 17. Interaction plot of Z-axis

3.7 Confirmation test

This confirmation test (Table 9) was conducted to evaluate the optimization of 3D printing parameters in improving the dimensional accuracy of bolts along the X, Y, and Z axes. The test results showed that a specific parameter combination yielded average dimensions close to the target values: 11.73 mm (X), 7.08 mm (Y), and 21.08 mm (Z). The measurement procedure for the confirmation test specimen along the X-axis is illustrated in Fig. 18. Furthermore, this confirmation test was carried out to verify that the identified optimal parameter combination is capable of achieving improved dimensional accuracy in product measurements along the X, Y, and Z axes, which have not been comprehensively addressed in previous studies [5], [6], [8], [17]-[19]. Therefore, the results of this research are expected to provide a reliable scientific reference for future studies aimed at developing and refining optimal process parameters.

Table 9. Confirmation test

Exp.	Axis	Optimum Process Parameters	Replication 1 (mm)	Replication 2 (mm)	Replication 3 (mm)	Average (mm)
1	X	Layer Height: 0.1 mm Infill Density: 95% Print Speed: 35 mm/s Nozzle Temperature: 205°C	12.01	12.01	11.17	11.73
2	Y	Layer Height: 0.08 mm Infill Density: 100% Print Speed: 45 mm/s Nozzle Temperature: 215°C	7.01	7.13	7.10	7.08
3	Z	Layer Height: 0.1 mm Infill Density: 100% Print Speed: 40 mm/s Nozzle Temperature: 210°C	21.07	21.08	21.08	21.08

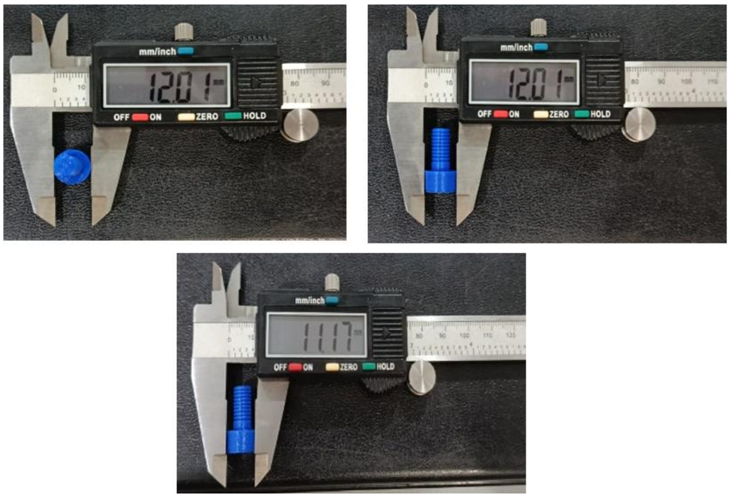


Fig. 18. The measurement process of the X-axis confirmation test specimen

Meanwhile, the measurement process for the Y-axis confirmation test specimen is illustrated in Fig. 19, and that for the Z-axis confirmation test specimen is shown in Fig. 20. These findings confirm that adjusting specific parameters for each axis effectively enhances the dimensional precision of 3D-printed components.

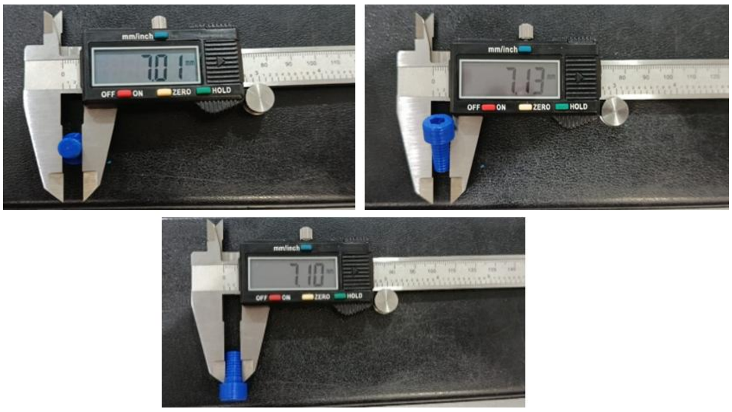


Fig. 19. The measurement process of the Y-axis confirmation test specimen

The results indicate that optimizing printing parameters, such as print speed, layer height, nozzle temperature, and infill, significantly affects dimensional accuracy. Optimal settings can reduce printing defects and improve precision compared to standard parameters in FDM CoreXY technology [21]-[23].

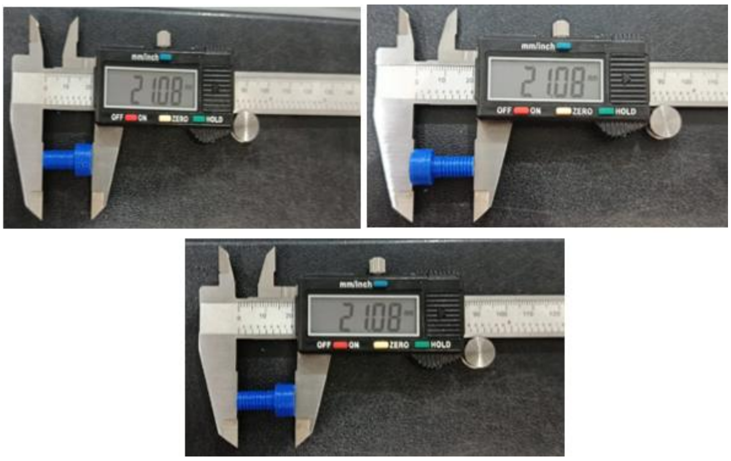


Fig. 20. The measurement process of the Z-axis confirmation test specimen

4 Conclusion

This study demonstrates that FDM process parameters significantly affect the dimensional accuracy of 3D-printed parts. Optimal conditions were achieved with a layer height of 0.1 mm, 100% infill, a print speed of 40 mm/s, and a nozzle temperature of 210 °C. Confirmation tests under these settings produced average dimensions close to the target values: 11.73 mm on the X-axis, 7.08 mm on the Y-axis, and 21.08 mm on the Z-axis. This indicates that parameter optimization can improve both the precision and consistency of dimensions in PLA+ 3D-printed products. Furthermore, the factors most affecting print quality are nozzle temperature and print speed, with the best performance observed at a combination of 95–100% infill, 0.2 mm layer height, 210°C nozzle temperature, and 20–30 mm/s print speed, yielding the most stable and optimal print quality while also suggesting interactions between process parameters.

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