

## Integration of taguchi method and digital metrology for precision fused deposition modelling of PLA-based vibration-damping components

Danang Yudistiro<sup>1\*</sup>, Salahuddin Junus<sup>2</sup>, Dani Hari Tunggal Prasetyo<sup>3</sup>, Istiqomah Rahmawati<sup>4</sup>, Helda Wika Amini<sup>5</sup>, Meta Fitri Rizkiana<sup>6</sup>

<sup>1</sup> Department of Mechanical Engineering, University of Jember, Jember 68121, Indonesia

<sup>2</sup> Chemical Engineering Study Program, University of Jember, Jember 68121, Indonesia

\*Corresponding author: [danang.ft@unej.ac.id](mailto:danang.ft@unej.ac.id)

### Abstract

This study integrates the Taguchi method and 3D digital metrology to improve dimensional accuracy in the Polylactic Acid (PLA)-based Fused Deposition Modelling (FDM) process. The research focuses on the fabrication of vibration-damping roller components in a Continuously Variable Transmission (CVT) system that demands high geometric precision. A Taguchi L9 experimental design was used to analyze the effects of layer height, extrusion temperature, and filling density on the volume deviation of the printed product. The evaluation was conducted using 3D scanning and analyzed using the Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA). The optimal parameter combination was obtained at a layer height of 0.25 mm and an extrusion temperature of 220 °C, resulting in the minimum volume deviation and the highest process stability. The ANOVA results identified layer height as the most dominant factor, followed by extrusion temperature, while filling density had a relatively small effect. Validation tests showed good agreement between the predictions and the experimental results. These findings confirm the effectiveness of integrating the Taguchi method with digital metrology in supporting the development of PLA-based precision additive manufacturing for sustainable automotive component applications.

### Keywords:

Additive Manufacturing, Fused Deposition Modelling (FDM), Polylactic Acid (PLA), Taguchi method, dimensional accuracy

## 1 Introduction

The development of the manufacturing industry over the past decade has shown a shift towards more flexible production technologies, one of which is additive manufacturing [1], [2], [3], [4], [5]. This technology enables the manufacture of components with complex geometries without the need for conventional molds or tooling, making it a promising solution for industrial sectors that demand high efficiency and customization [6], [7], [8], [9], [10]. Among the various additive manufacturing approaches, Fused Deposition Modelling (FDM) stands out for its simplicity, low operational costs, and ease of material acquisition [5], [11], [12], [13], [14]. However, dimensional accuracy in FDM-produced products remains a major challenge, due to complex interactions among process parameters, material thermal characteristics, and environmental conditions during printing [15], [16], [17], [18]. In this study, environmental conditions during the printing process

were controlled to remain relatively stable, so that the observed dimensional variations mainly reflect the influence of the process parameters under study.

Poly(lactic Acid) (PLA) is among the most widely used materials in FDM, primarily due to its ease of printing, biodegradability, and strong alignment with sustainability principles [19], [20], [21], [22], [23], [24], [25]. However, PLA is highly sensitive to changes in temperature and cooling rate, potentially leading to geometric distortion and volumetric deviation [26], [27], [28], [29]. This challenge is crucial in precision applications, such as vibration-damping rollers in Continuously Variable Transmission (CVT) systems, where any geometric deviation can affect the system's mass balance and dynamic performance [18], [30], [31], [32]. In this context, dimensional deviations not only affect the visual quality of the printed part but also carry important functional implications in precision applications such as CVT vibration-damping rollers, where even small geometric mismatches can alter the mass distribution and dynamic response, thus affecting the overall system behavior.

Previous studies have extensively discussed the optimization of FDM process parameters to improve the mechanical strength and surface quality of PLA prints. Ezathi and Sadeghi [33] used the Taguchi method to improve tensile properties, while Nazma et al. [34] integrated the CRITIC-EDAS method for multi-criteria analysis, but neither method addressed spatial shape deviation. The ANFIS-WOA approach by Sai et al. [35] focused on surface roughness and printing time. At the same time, a review by Sandanamsamy et al. [36] emphasized the importance of parameter control in printing high-quality PLA. Despite their significant contributions, most studies are still limited to two-dimensional evaluation and have not integrated quantitative three-dimensional geometric validation. This reinforces the urgency of an integrative approach between statistical optimization and 3D digital metrology, as proposed in this study.

To address this challenge, this study proposes integrating the Taguchi method as a statistical optimization framework with 3D digital metrology. Taguchi was chosen for its ability to identify dominant parameters and assess system stability through the Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA) [37], [38], [39]. Meanwhile, the digital metrology approach enables volumetric evaluation and spatial validation of optimization results. The combination of these two methods not only assesses deviation but also reveals the causal relationship between process variables and shape deviation, which has previously been poorly quantified.

By focusing on geometric precision, production efficiency, and material sustainability, this study aims to make a significant contribution to the development of PLA-based FDM systems for industrial applications. This approach is expected to strengthen the scientific foundation for precision additive manufacturing process design and offer a practical alternative to support the transition to a sustainable automotive industry.

## 2 Methodology

This study employs a statistically based controlled experiment to identify the optimal parameter combination for the FDM process using PLA material. The primary focus of this experiment is to achieve robust optimization of the dimensional accuracy of printed vibration-damping roller components for a CVT system by minimizing volumetric deviation and its variability. The research design employed the Taguchi method with an L9 (3<sup>3</sup>) orthogonal matrix, which enables three-factor analysis at three levels without compromising statistical validity [40]. The Taguchi method was chosen for its efficiency in reducing the number of experiments while minimizing the influence of random variables on the response results [41].

The material used in this study was a commercially available PLA filament with a nominal diameter of 1.75 mm and a material density of 1.24 g/cm<sup>3</sup>. PLA was chosen for its readily

biodegradable characteristics, low mass density, and relatively stable dimensional behavior at moderate processing temperatures. To maintain consistency throughout the experiment, all specimens were fabricated using a fixed printing speed of 50 mm/s. Three-dimensional validation and volumetric assessment were performed using an EinScan-SE structured-light 3D scanner. The production process was operated through EinScan's Shining 3D software, which is freely distributed with the scanner system and is widely used in digital metrology applications. To isolate the dominant thermogeometric influence on dimensional accuracy, only three FDM process parameters, layer height, extrusion temperature, and infill density, were systematically varied. Other printing parameters, including nozzle diameter, printing plate temperature, cooling conditions, raster pattern, and shell thickness, were intentionally kept at constant values in accordance with the Taguchi L9 experimental framework. Before the entire series of experiments, the 3D printer was calibrated to ensure dimensional consistency and stability of the printing process. Extruder calibration was performed by verifying the extrusion stroke value (extruder strokes per millimetre) using a 100 mm filament extrusion test. Nozzle condition was checked through visual inspection and material flow tests to ensure there were no partial blockages or irregularities in the filament flow. The print bed levelling process was performed manually using the four-point method to ensure a uniform nozzle distance from the print bed surface throughout the work area. The initial layer distance was measured using a paper-like thickness gauge to ensure consistent first-layer adhesion. The geometric model of the vibration-damper roller was developed in SolidWorks 2023. After fabrication, the scanned dataset was spatially aligned with the reference CAD model, and the volumetric deviation was evaluated using the volume calculation and point-to-point distance measurement functions in the EinScan software environment. The comparison between the measured print volume and the nominal CAD volume was then used to determine the Percentage of Print Volume (PPV). The geometric dimensions of the vibration damper (roller) are presented in Fig. 1.

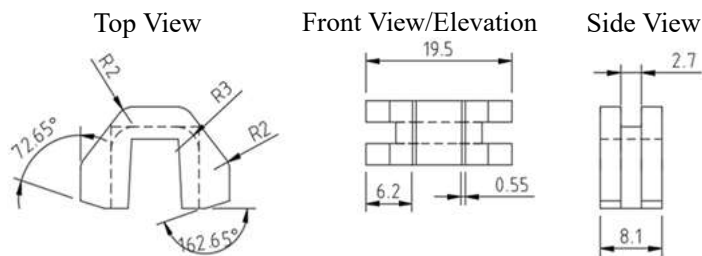


Fig. 1. Geometric dimensions of vibration-damping rollers (all sizes in mm)

The three process parameters investigated in this study, layer height, extrusion temperature, and infill density, were selected based on their fundamental and interrelated roles in governing thermomechanical behavior and geometric fidelity in the PLA-based FDM process. Layer height directly controls geometric resolution and interlayer heat accumulation, while extrusion temperature governs melt viscosity and interfilament diffusion. Infill density influences internal material distribution and volumetric stability. Collectively, these parameters constitute the primary thermogeometric variables that determine dimensional accuracy in extrusion-based additive manufacturing. It is well known that dimensional accuracy in FDM is affected by a wider range of process variables, including printing speed, raster orientation, cooling conditions, and nozzle diameter, as widely reported in the literature. However, in this study, these secondary parameters were intentionally kept constant to isolate and quantify the dominant effects of layer height, extrusion temperature, and infill density on volumetric deviation. This selection strategy was further aligned with the Taguchi L9 orthogonal array, which was specifically designed to efficiently identify influential factors while ensuring statistical robustness and experimental feasibility. By limiting non-critical variables, experimental design enables a focused investigation of the key parameters most relevant to dimensional accuracy optimization. These three parameters were selected based on previous studies demonstrating their dominant influence on material deposition behavior, thermal diffusion, and interlayer bonding, which collectively govern dimensional accuracy and print quality in PLA-based FDM processes. Each parameter was tested at three levels, as shown in Fig. 2.

Each parameter combination was printed three times to ensure consistent results and reduce the influence of experimental uncertainty. After printing was complete, all specimens were allowed to cool naturally under laboratory conditions for 30 minutes before dimensional measurements were performed. This cooling time was set to ensure the PLA material reached a thermally stable state and to minimize the effect of thermal relaxation and post-printing shrinkage on the measurement results. Based on initial observations during the experiment and common practice in PLA-based FDM printing, dimensional changes due to passive cooling become insignificant after 20–30 minutes. Therefore, a 30-minute duration was chosen and applied consistently across all specimens to maintain uniformity of measurement conditions

No of Tests	Layer Height (mm)	Extrusion Temperature (°C)	Fill Density (%)
1	0.20	200	60
2		210	70
3		220	80
1	0.25	200	70
2		210	80
3		220	60
1	0.30	200	80
2		210	60
3		220	70

Fig. 2. The Taguchi L9 (3<sup>3</sup>) experimental matrix used in the study was compiled using Minitab 19

All experiments were conducted in a laboratory with a controlled temperature ( $\pm 25^\circ\text{C}$ ) and stable humidity below 60%. The initial stage included printer calibration, nozzle verification, and bed levelling to ensure uniformity of the first layer. After the 3D model was printed, the specimen was allowed to cool naturally for 30 minutes before measurements were taken.

The prints were then scanned using a 3D scanner, producing STL files that were compared with the original CAD model. The difference between the printed volume and the design volume was calculated using Eq. (1).

$$PPV = \frac{|V_p + V_d|}{V_d} \times 100\% \quad (1)$$

where  $V_p$  represents the actual volume of the printed specimen obtained from 3D scanning, and  $V_d$  denotes the nominal volume of the reference CAD design. The Percentage Change in Volume (PPV) value is used as an indicator of dimensional accuracy; the smaller the value, the more precise the print results are to the reference design. Data analysis was performed using Minitab 19 software. The first stage is the calculation of the S/N ratio with the smaller-is-better characteristic, which is used to determine the parameter combination with the smallest variation in results, with the equation that can be observed in Eq. (2).

$$\frac{S}{N} = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \quad (2)$$

where  $Y_i$  represents the PPV value measured for the  $i$ -th experimental run, and  $n$  denotes the number of repetitions. An ANOVA was then performed to assess the influence of each factor on the response using a 95% significance level. The F-value, p-value, and relative contribution ( $\eta^2$ ) were used to determine the most dominant factor influencing volume deviation.

The statistical model was then tested for validity through residual analysis, which comprises three components.

- Autocorrelation Function (ACF) to ensure data independence
- Residual versus fit plot to check for homogeneity of variance
- Kolmogorov–Smirnov test to test for normality of the error distribution

If all assumptions are met, the ANOVA results are considered valid and can be used to formulate the optimal parameter combination. After the optimum parameter combination is obtained from the S/N calculation and ANOVA, a confirmatory experiment is conducted to verify the accuracy of the model predictions. The PPV value from the confirmatory test is compared with the predicted value and the model's 95% confidence interval. The difference between the two is calculated to determine the absolute prediction error, which is used as a benchmark for the reliability of the Taguchi method in the context of PLA-based additive manufacturing.

This research method is systematically designed to ensure the reliability of the experiment, the validity of the analysis, and the replicability of the results. The integration of Taguchi-based statistical optimization and spatial verification via 3D digital metrology results in a comprehensive approach in understanding the influence of process factors on the geometric accuracy of FDM molds. With this method design, the research not only contributes to improving the precision of PLA-based additive manufacturing but also supports the development of sustainable precision manufacturing practices at the scale of the modern automotive industry.

### 3 Results and discussion

#### 3.1 Process performance and print characteristics

All volumetric data analyzed in this section were obtained through a calibrated 3D scanning process. Therefore, variations in measurement results reflect the influence of printing process parameters, not the uncertainty of the measuring instrument. Numerical evaluation of the printing process results shows a fairly stable agreement between the actual volume of the specimen and the design in the CAD model. The PPV deviation values obtained from nine experimental combinations show a narrow deviation range, indicating that the deposition system in the PLA-based FDM process operates under controlled conditions. Changes in the PPV value and S/N ratio show a direct relationship between variations in layer height, extrusion temperature, and fill density levels on the dimensional accuracy of the printed results. Detailed data on volume, geometric deviation, and process stability are listed in Table 1, and a visualization of the printed slide piece results compared to the CAD design is shown in Fig. 3.

Table 1. Results of measurements of volume and dimensional deviation of PLA print results

No of test	Layer height (mm)	Temperature ( $^\circ\text{C}$ )	Fill density (%)	Volume ( $\text{mm}^3$ )	PPV (%)	S/N (dB)
1	0.20	200	60	1047.37	12.77	-23.30
2	0.20	210	70	1050.69	13.12	-22.54
3	0.20	220	80	1011.16	8.87	-19.14
4	0.25	200	70	976.83	5.17	-14.28
5	0.25	210	80	1011.16	8.87	-18.96
6	0.25	220	60	966.17	4.02	-13.20
7	0.30	200	80	1008.24	8.55	-18.74
8	0.30	210	60	1047.09	12.74	-22.17
9	0.30	220	70	1020.48	9.87	-19.99

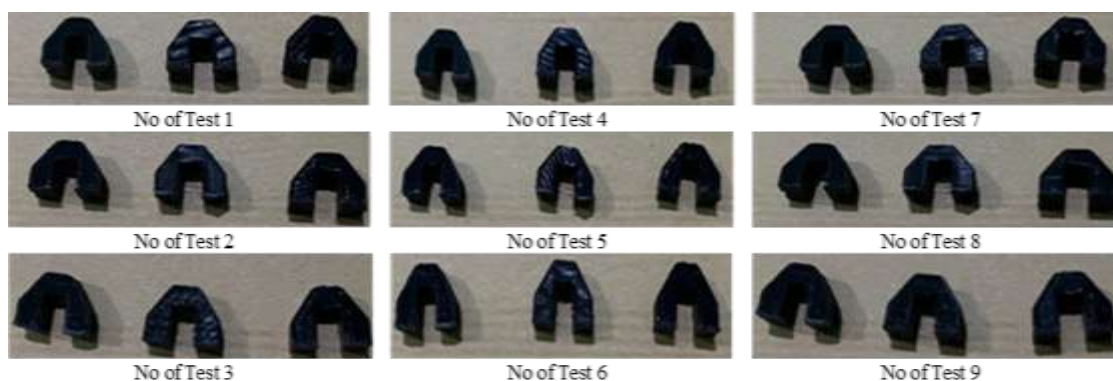


Fig. 3. Slide piece product results using 3D printing

Based on the results presented in Table 1, all printed specimens exhibited a positive volumetric deviation relative to the nominal

CAD geometry, with PPV values ranging from 4.02% to 13.12%. This systematic increase in volume reflects an inherent tendency

toward overbuilding in the FDM process, which is generally associated with thermal expansion during filament deposition followed by non-uniform shrinkage during cooling. The highest deviation was observed for the parameter combination of a 0.20 mm layer height and an extrusion temperature of 210 °C. Under this condition, excessive heat accumulation in thin deposited layers is likely to delay solidification, allowing lateral flow of the molten filament and subsequent widening of the deposited bead. Comparable trends have been documented in prior studies, where reduced layer thickness was shown to enhance local heat retention near the nozzle, resulting in filament spreading, increased bead width, and dimensional overshoot before complete solidification [15], [22], [23], [42].

In contrast, when a larger layer height of 0.30 mm was used at elevated extrusion temperatures, a fully bonded interlayer structure was not formed. This condition is associated with increased molten material volume deposited in each pass, altering the thermal residence time available at the layer interface. Although the nozzle temperature provides sufficient thermal energy at the point of deposition, the thicker filament cross-section requires a longer period for heat to propagate through the deposited layer and activate polymer chain mobility across the interlayer boundary. Consequently, cooling initiates before adequate molecular interdiffusion can occur, resulting in weakened interlayer cohesion. As shown in Fig. 3, the printed specimen maintains an overall geometric conformity with the CAD model; however, the absence of visible distortion does not rule out localised limitations in interlayer fusion.

The combination of a layer height of 0.25 mm, a nozzle temperature of 220 °C, and a fill density of 60% resulted in a PPV of 4.02% and an S/N of -13.20 dB. From a thermal perspective, the increase in extrusion temperature reduced the melt viscosity of PLA, which, under the controlled printing conditions adopted in this study, facilitated enhanced molecular mobility and interlayer diffusion rather than excessive material flow. Although lower viscosity is often associated with dimensional inaccuracy due to filament spreading, this effect becomes dominant primarily when thermal input is excessive or when solidification kinetics are insufficiently balanced. In the present case, the elevated temperature promoted improved wetting and intimate contact at the interlayer interface, allowing polymer chains to interdiffuse before cooling-induced solidification occurred. This mechanism strengthened interlayer bonding and mitigated geometric instability, ultimately resulting in improved dimensional consistency rather than increased inaccuracy. These findings align with those reported by Li et al. [43] and Stojković et al. [42], who emphasized layer height and nozzle temperature as key determinants of dimensional accuracy in FDM-PLA, as well as with those of Hungria et al. [44] and Kumar et al. [45], who demonstrated that increasing the

extrusion temperature improves interlayer bonding through neck growth and intermolecular diffusion.

In the application context, dimensional accuracy is crucial for controlling the mass distribution of CVT vibration-damping rollers. The optimal parameter combination obtained in this study suppressed the volume deviation to  $\pm 4\%$ . The volume deviation was compared to the nominal CAD geometry without sacrificing printing efficiency, under the same operating conditions. This efficiency was maintained because the deposition speed was kept constant throughout the test. This certainly affects the difference in printing duration, especially with geometric factors, one of which is layer thickness. Thus, the improvement in geometric accuracy was achieved by controlling geometric and thermal parameters without increasing manufacturing time due to an excessive number of layers. Since printing speed was not varied in this study, the observed performance improvement mainly reflects the effectiveness of layer thickness and extrusion temperature optimization in stabilizing the deposition process and improving interlayer bonding. Therefore, the proposed parameter configuration shows strong potential for application in PLA-based precision additive manufacturing, especially for automotive components that demand tight dimensional tolerances and consistent mass distribution.

To strengthen the practical relevance, the results of the study were compared descriptively with the CVT vibration-damping roller used in the actual system. Based on the available reference component dimensional information, the volumetric values of the PLA-based roller printed using the optimal parameters in this study were in a comparable range. The results of this comparison indicate that the proposed parameter configuration is capable of producing components with geometric consistency close to the original components, thus potentially being applied to CVT systems without significant geometric changes.

### 3.2 Quantitative analysis of volume deviation and S/N ratio

Quantitative analysis was conducted to evaluate the influence of three main parameters: layer height, extrusion temperature, and fill density on the dimensional deviation of PLA printed specimens. Two metrics were used as process performance indicators: PPV to measure geometric accuracy and S/N to represent manufacturing process stability. The average values per factor level are presented in Fig. 4.

In Fig. 4, it can be observed that layer height has the most significant influence on geometric accuracy. The highest PPV value was recorded at 0.20 mm at 11.59%, while the lowest value was obtained at 0.25 mm at 6.02%, accompanied by the best S/N ratio of -15.48 dB. This indicates that intermediate layer thicknesses produce the best dimensional stability. Accuracy decreased to 0.30 mm with a PPV value of 10.39%.

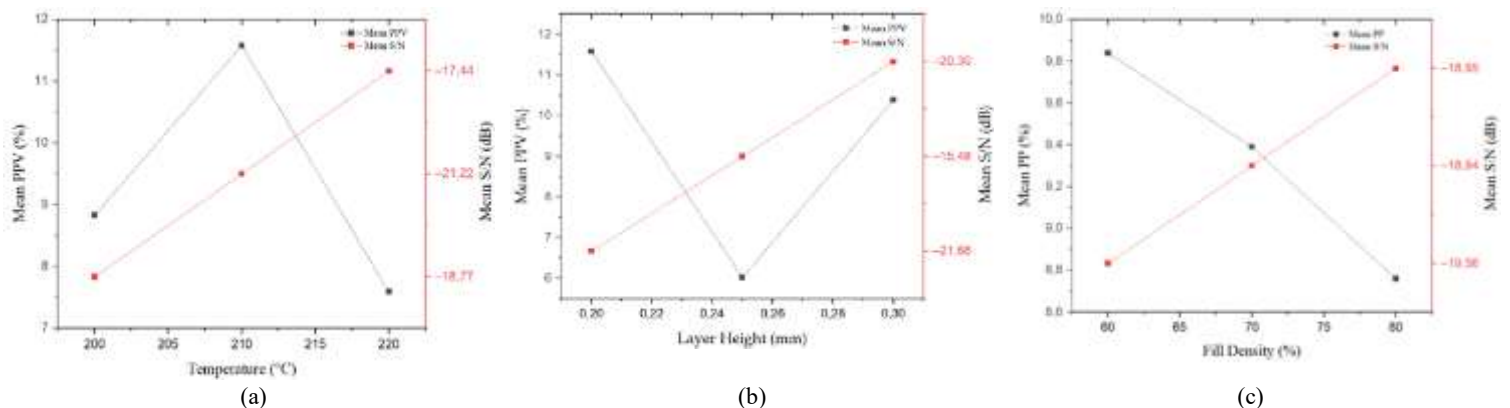


Fig. 4. Main effects of factors (a) temperature, (b) layer height, and (c) fill density on PPV and S/N

This indicates that too thick a layer hinders interlayer bonding due to reduced thermal diffusion time [15], [22], [42]. In the temperature parameter, a similar trend is seen. Increasing the temperature from 200°C to 220°C decreased the PPV from 8.83%

to 7.59% and increased the S/N from -18.77 dB to -17.44 dB, indicating more optimal material fusion conditions. A temperature of 210°C actually produced the highest PPV of 11.58%, likely

because the material's viscosity was not low enough to ensure uniform flow and adhesion.

On the other hand, changes in the fill density value only resulted in very small variations in the quantitative evaluation results. The PPV ranged between 9.84% and 8.76%, while the S/N ratio remained relatively stable at around -19 dB. This condition indicates that the fill density did not significantly affect the final mold volume. These results reinforce the view that fill density plays a greater role in determining total weight and internal mechanical strength than geometric shape accuracy. This finding aligns with the research of Singh et al. [46], who reported that infill density contributed the least to dimensional accuracy among key parameters such as layer height and extrusion temperature in printing distal femur bone models using the Taguchi method. In line with this, Aiman et al. [47] also found that while variables such as raster angle and layer thickness significantly affect surface roughness and shape accuracy, infill density mainly influences mass-related characteristics and internal structural strength, with only a marginal impact on geometric deviation. Overall, the results of this study confirm that layer height and extrusion temperature are key factors in maintaining dimensional consistency and stability in PLA-based FDM printing. At the same time, fill density plays a secondary role that remains important in designing the structural strength of mechanical components.

### 3.2.1 Direct effect of parameters on dimensional deviation

Of the three parameters analyzed, layer height was the most dominant factor in determining the geometric accuracy of the printed results. A thickness of 0.25 mm resulted in the lowest volume deviation (PPV = 6.02%) and the highest stability ratio with an S/N value of -15.48 dB, indicating that in this configuration, there is a balance between material volume, cooling time, and melt flow between layers. When the thickness is reduced to 0.20 mm, the PPV value jumps to 11.59% in the S/N decreases to -21.66 dB, due to local heat accumulation that causes lateral expansion of the melt before solidification [48], [49]. An increase to 0.30 mm also negatively impacts PPV, resulting in a value of 10.39% and an S/N of -20.30 dB, which is suspected to be caused by limited diffusion time and weak interlayer cohesion [50], [51]. These findings indicate the existence of a geometric optimum point, where deviations occur when the layer thickness is too low or too high. The extrusion temperature parameter shows a nonlinear effect on dimensional deviation. At 200°C, the accuracy is moderate with a PPV of 8.83% and an S/N of -18.77 dB. However, when the temperature is increased to 210°C, the performance decreases significantly with a PPV of 11.58% and an S/N of -21.22 dB. This indicates that the material viscosity is not low enough to support interfilament fusion. A temperature of 220°C gives the best results with a PPV of 7.59% and an S/N of -17.44 dB. This indicates that high temperature plays an important role in improving material flow and increasing molecular bonding between layers.

In contrast, the effect of fill density on dimensional accuracy is relatively small and insignificant. The difference in PPV between levels is only ±1%, and the S/N value tends to remain constant at -19 dB. Therefore, this parameter is categorized as a secondary factor in the context of geometry control in PLA-based FDM processes. These findings indicate the presence of a geometric optimum, where dimensional deviation increases when the layer thickness deviates either below or above an intermediate value. A comparable non-linear response is also observed for the extrusion temperature parameter, reinforcing the role of thermogeometric balance in controlling dimensional accuracy. At 200 °C, moderate accuracy is achieved, with a PPV of 8.83% and an S/N ratio of -18.77 dB. Increasing the temperature to 210 °C leads to a pronounced deterioration in performance, as reflected by a higher PPV of 11.58% and a lower S/N value of -21.22 dB, suggesting that the melt viscosity at this condition remains insufficient to ensure stable interfilament fusion.

In contrast, further increasing the temperature to 220 °C results in the lowest dimensional deviation (PPV = 7.59%) and the highest process stability (S/N = -17.44 dB), indicating that enhanced material flow and molecular mobility promote more effective interlayer bonding. In comparison with the strong non-linear effects observed for layer height and extrusion temperature, the influence of fill density on dimensional accuracy is relatively limited. Variations in PPV across the investigated fill density levels remain within approximately ±1%, while the corresponding S/N values show minimal fluctuation around -19 dB. This behavior suggests that fill density primarily governs internal material distribution and structural integrity rather than external geometric fidelity. Consequently, fill density can be classified as a secondary parameter in the context of geometric accuracy control for PLA-based FDM processes.

### 3.2.2 Interaction of geometric and thermal parameters

The analysis of the interaction between layer height and extrusion temperature shows that the combined effect of both parameters is not always linear or mutually reinforcing. Based on the data in Table 2, the combination of a layer height of 0.25 mm and a temperature of 220°C produced the best results, with the smallest dimensional deviation, with a PPV value of 4.02% and the highest stability, with an S/N value of -13.195 dB. This condition indicates that this configuration achieves an optimal balance between melt pressure, diffusion time, and layer cooling. The interaction matrix of layer height and temperature on PPV and S/N can be seen in Table 2.

Table 2. Interaction matrix of layer height and temperature on PPV and S/N

LH / Temp. (°C)	S/N (dB)			PPV (%)		
	200	210	220	200	210	220
0.20	-23.304	-22.536	-19.141	12.77	13.12	8.87
0.25	-14.282	-18.964	-13.195	5.17	8.87	4.02
0.30	-18.740	-22.172	-19.993	8.55	12.74	9.87

At a layer height of 0.20 mm, increasing the temperature from 200°C to 210°C actually increases the deviation, with the PPV increasing from 12.77% to 13.12%, and the stability decreases, with an S/N value of -22.536 dB. However, when the temperature is increased to 220°C, the deviation decreases with a PPV of 8.87%, and the process becomes more stable with an S/N of -19.141 dB. This pattern indicates that high temperatures can improve the printing performance of thin layers, but only if the temperature is sufficient to reduce flow resistance and accelerate interlayer fusion. Conversely, for a layer height of 0.30 mm, the results tend to be inconsistent. At 210°C, the deviation reaches its highest point, with a PPV value of 12.74%, and stability is also low with an S/N of -22.172 dB. Even at 220°C, the performance still does not improve significantly. This indicates that increasing the temperature is not always sufficient to stabilize excessively thick layers, due to diffusion limitations and insufficient time for full intermolecular cohesion to form.

This overall pattern demonstrates that the interaction between parameters is stronger than the effect of each parameter alone. Adjusting one parameter without adjusting the others can actually worsen the results. Therefore, FDM process optimization cannot be performed one-dimensionally; it must consider overall thermal and geometric synchronization.

### 3.2.3 Relative contribution of factors (ANOVA)

To measure the significance of the contribution of each parameter, ANOVA was performed, and the results are shown in Table 3.

Table 3. ANOVA Contribution

Factor	Sum of Squares (SS)	$\eta^2$ (%) = (SS / Total SS) × 100
Layer height	632.744	64.6%
Extrusion temperature	220.376	22.5%
Fill density	0.7566	0.8%

Residual (uncontrolled)	11.859	12.1%
Total	979.276	100%

Layer height accounted for 64.6% of the total variation, confirming its dominance in controlling geometric accuracy. Extrusion temperature contributed 22.5%, while fill density only 0.8%, and can be considered statistically insignificant. The remaining 12.1% variation is classified as residual. This is suspected to originate from environmental factors, machine variations, or optical measurement errors. The analysis results showed that the combination of a layer height of 0.25 mm and a temperature of 220°C provided the best performance in terms of deviation and print stability. The fill density parameter had a limited effect on dimensional accuracy. Therefore, FDM process optimization should focus on adjusting layer thickness and extrusion temperature, taking into account their interactions, to produce precise, reproducible PLA prints.

### 3.3 Model validation and confirmation test

ANOVA was applied to assess the extent to which each process parameter contributed to dimensional fluctuations in the printed output. Based on Table 4, layer height was the most influential factor, contributing 53%, and fill density had almost no effect at 1%. The remaining 36% of the variation was categorized as residual error, likely influenced by external factors such as ambient temperature fluctuations, cooling fan instability, and limitations of the optical scanning system.

Table 4. Results of ANOVA on S/N Ratio

Variabel	DF	SS	MS	F-value	P-value	$\eta^2$ (%)
Layer height	2	63.2744	31.6372	5.3356	0.157	53%
Extrusion temperature	2	220.376	11.0188	1.8583	0.349	10%
Fill density	2	0.7566	0.3783	0.0638	0.94	1%
Residual error	2	11.859	5.9295			36%
Total	8	97.9276				100%

Although the F-count for layer height (5.34) has not yet reached the threshold of statistical significance (F-table = 19.00;  $\alpha = 0.05$ ), its dominant contribution cannot be practically ignored. This fact shows that layer thickness variations directly affect the print volume deviation, more strongly than thermal or internal structural variables. The sharply decreasing contribution distribution pattern also indicates that efforts to optimize print quality should focus on adjusting the layer height, while adjusting the fill density has only a

Table 5. Comparison of Predicted Values and PPV Experiments

No	Layer height (mm)	Extrusion Temp. (°C)	Fill density (%)	PPV prediction (%)	Experimental PPV (%)
1	0.20	200	60	12.77	12.77
2	0.20	210	70	13.12	13.12
3	0.20	220	80	8.87	8.87
4	0.25	200	70	5.17	5.17
5	0.25	210	80	8.87	8.87
6	0.25	220	60	4.02	4.09
7	0.30	200	80	8.55	8.55
8	0.30	210	60	12.74	12.74
9	0.30	220	70	9.87	9.87

The strong agreement between the predicted results and the experimental test data indicates that the Taguchi-based optimization approach, when applied in conjunction with a digital metrology-based geometric measurement system, can provide precise and stable dimensional deviation estimates. The collaboration of these two methods underscores the effectiveness of applying statistical analysis in the FDM process with PLA material, especially in high-precision additive manufacturing applications such as the manufacture of vibration-damping components for CVT transmission systems. These results are in line with the study by Chen [52], which proved that combining the Taguchi method with response surface analysis can improve the quality of printed results by optimizing process parameters, including layer thickness and nozzle temperature. In line with this, Petrusse et al. [53] also stated

marginal impact on dimensional accuracy. The results of the ANOVA on the S/N Ratio in Table 4 confirm this finding, with layer height visually dominating the contribution bar chart. Thus, focusing process control on the main geometric aspects is more efficient than a simultaneous approach to all parameters.

### 3.3.1 Statistical model validation

Model validation was performed through residual analysis to ensure that the classical statistical assumptions were met. The ACF results showed that there was no periodic pattern or autocorrelation in the residuals, indicating that the data were independent. The plot of residuals against predicted values showed a random distribution without any particular pattern, indicating that the assumption of homoscedasticity was met. Furthermore, the Kolmogorov–Smirnov test produced a p-value of 0.150 ( $> 0.05$ ), confirming that the residuals were normally distributed. Thus, all Independent, Identically Distributed, and Normal (IIDN) distribution assumptions were met, and the statistical model used was declared valid and reliable for predicting dimensional deviation in the PLA-based FDM process.

In addition to residual analysis, the adequacy of the statistical model was assessed by evaluating its coefficient of determination. The resulting  $R^2$  value indicated that most of the observed variation in the response was effectively captured by the selected process parameters. To address the influence of model complexity and sample size, the adjusted coefficient of determination,  $R^2(\text{adj.})$ , was also examined and showed close agreement with  $R^2$ , indicating that the model was not overfit. Furthermore, the predictive coefficient,  $R^2(\text{pred.})$ , showed comparable levels, confirming that the model maintained sufficient predictive ability to estimate volumetric deviations in the PLA-based FDM process. Therefore, the agreement between  $R^2$ ,  $R^2(\text{adj.})$ , and  $R^2(\text{pred.})$  supports the robustness and reliability of the proposed statistical model.

### 3.3.2 Confirmation test and prediction accuracy

To verify the model's performance, a confirmation test was conducted using the optimal parameter combination: layer height 0.25 mm, extrusion temperature 220°C, and fill density 60%. The experimental test results yielded an actual PPV of  $4.09\% \pm 0.15$ , within the 95% confidence interval of the predicted model. A comparison of the predicted and experimental PPV values is shown in Table 5.

that the balance between thermal and geometric factors, including print speed, layer thickness, and nozzle diameter, plays an important role in maintaining the shape accuracy and robustness of thermoplastic material layers. Therefore, the integration of statistical optimization strategies with digital metrology validation has proven effective in suppressing geometric variations and increasing the reliability of 3D print quality predictions.

### 3.4 Physical interpretation and engineering implications

Dimensional precision in the PLA FDM process is significantly influenced by the stability of thermomechanical parameters during printing. A layer thickness of 0.25 mm has proven to be the optimal configuration, as it maintains a balance between surface resolution and thermal stability. Layers that are too thin ( $< 0.25$  mm) tend to cause local heat accumulation around the nozzle, widening the print

path and causing overbuilding. Conversely, layers that are too thick ( $>0.25$  mm) shorten the intermolecular diffusion time, resulting in weak interlayer cohesion and increased dimensional defects [54], [55]. At  $220^{\circ}\text{C}$ , the viscosity of the PLA melt decreases significantly, improving material flow rate and strengthening interphase bonding, resulting in more even fusion and more uniform cooling.

The low contribution of fill density (0.8%) to the deviation indicates that this parameter does not play a significant role in external shape formation but rather influences mass and mechanical response. In applications such as CVT vibration-damping rollers, mass uniformity between specimens is crucial to maintaining the dynamic balance of the transmission system. The ability to suppress volume deviation to  $\pm 4\%$  relative to CAD with an optimum configuration demonstrates the effectiveness of integrating the Taguchi method and digital metrology in maintaining geometric uniformity without sacrificing print efficiency.

Physically, this increased accuracy reflects the success in managing heat distribution and enhancing molecular diffusion between filaments. The reduced temperature gradient during deposition reduces residual thermal stress, while the increased intermolecular bonding results in a more homogeneous and dimensionally stable structure. These results emphasize the need to simultaneously control thermal and geometric parameters to maintain dimensional fidelity in PLA materials. The engineering implications of these findings are broad, as PLA, as an environmentally friendly biopolymer, has proven suitable for use in precision additive manufacturing, particularly in automotive components and lightweight mechanical systems. The statistical optimization-based approach, combined with digital metrology validation and physical process understanding, provides a robust and applicable framework for data-driven quality control. Therefore, this strategy has the potential to be adopted in industrial automation-based manufacturing systems that demand high efficiency and tight dimensional tolerances.

#### 4 Conclusions

The conclusions of the research on the integration of the Taguchi method and digital metrology for precision additive manufacturing of PLA-based vibration-damping components are as follows:

- a. Dimensional accuracy in the FDM process with PLA is highly dependent on the process parameters used during printing. Of the various combinations evaluated, a configuration with a layer thickness of 0.25 mm, an extrusion temperature of  $220^{\circ}\text{C}$ , and a fill density of 60% demonstrated the best performance with the lowest volumetric deviation. Statistical analysis identified layer thickness as the most significant factor affecting geometric accuracy, followed by extrusion temperature, while fill density showed a comparatively minor effect.
- b. The reliability of the developed model was confirmed. The test demonstrated good agreement between the predicted results and experimental data, validating the reliability of the Taguchi-based optimization model in describing the relationship between process parameters and volumetric deviation.
- c. The combined approach of statistical optimization and digital metrology-based validation enables dimensional control within  $\pm 4\%$  of the CAD model, without sacrificing time and material efficiency. This approach provides a practical and scalable framework for precision component manufacturing in additive processes.

Future research should evaluate the performance of the fabricated CVT vibration-damping roller under real operating and investigate temperature distribution and heat transfer during printing using numerical thermal simulations further.

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