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Enhancing Dimensional Accuracy of Affordable 3D-Printed Objects Via Solid Model Tuning For Industrial Manufacturing

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Abstract

In the industrial applications of 3D printing (3DP) technologies, achieving precise dimensional accuracy and precision as well as improving surface quality are essential goals. With a focus on cost-effective engineering applications, this experimental research examines how solid model geometry tuning improves the internal and exterior dimensional accuracy of inexpensive 3DP technologies. Dimensional errors in the X, Y, and Z directions were meticulously measured on 3D parts made using Material Extrusion/Fused Filament Fabrication (FFF) and Stereolithography (SLA)/Digital Light Processing (DLP), and these measurements were utilized for 3D model error correction by tuning. These measurements guided the refinement of subsequent solid models, resulting in significant improvements in the dimensional accuracy of low-cost SLA and FFF 3D-printed polymer material parts, making them suitable for use as direct products, dies, and patterns. A recently developed novel and simple error-tuning mathematical model is experimentally validated in this study and addresses internal and external dimensions based on measured linear directional errors (e_i, e_j, and e_k). This approach provides a flexible approach for achieving higher dimensional accuracy across various 3D printing processes. This work addresses crucial challenges in low-cost SLA and FFF processes, offering new insights and solutions for improving accuracy in future engineering applications of these technologies.

Keywords: Rapid casting, polymer pattern, additive manufacturing, low-cost 3D printing, dimensional accuracy, sustainable manufacturing

INTRODUCTION

In the 1980s, 3D Systems Inc. CA[1] pioneered basic 3D printing (3DP), also known as rapid prototyping (RP), which is a generative manufacturing process that builds objects layer by layer. Initially, 3DP was popular among architects and designers for creating prototypes due to its accessibility. Recently, its use has expanded to various environments, including schools, homes, offices, libraries, and labs, largely because of its affordability. The assessment of technology and materials in 3DP facilitates the direct manufacturing (DM)[2] of safe, robust, and lightweight products, offering just-in-time production with production cost optimization. As part of the present industrial revolution(industry 4.0), additive manufacturing (AM) and 3DP are thriving research fields, enabling the creation of advanced industrial products and even artificial human organs directly from 3D models.

Futuristic technological advantages of 3D printing include the ability to build complex internal and external geometries that are not possible with other manufacturing processes [3], nano-micro

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assembly capacity, and the ability to process a wide range of materials such as bio-materials, polymers, metals, alloys, and ceramics. It also offers effective customization[4], reduces material wastage, and can improve fuel efficiency with lightweight parts. Additionally, 3D printing saves space and costs by eliminating the need for large stock inventories, reduces lead times, and decreases raw material consumption. The aforementioned attributes represent the salient qualities of this state-of-the-art technology [5], rendering it a foundational element of Industry 4.0 [6].

It has the potential to eliminate the high costs associated with product customization and personalization[4]. It also reduces lead times for critical replacement of components in on-demand production, shortens supply chains, enhances response times, and lowers storage and shipping expenses[3].

Industrial Applications of 3D Printing

Additive Manufacturing (AM) is experiencing rapid growth across industrial sectors, with demand nearly quadrupling over the past five years. In 2020, 47% of the world's 3D printed items were prototypes, 21% were jigs and fixtures, 29% were functional and aesthetically pleasing, and 3% were other parts[7].

3D printing and Rapid Casting (RC) or Rapid Investment Casting (RIC) hybrid processes are effectively utilized in the production of components for a wide range of applications, including but not limited to aerospace engines, robotic components, airframes, automotive parts, bicycles, agricultural machinery, textile equipment, and dental instruments[8]. They are also employed in the manufacturing of electrical devices, cameras, radar systems, firearms, jewellery, machine tools, prosthetics, high-pressure pumps, sports equipment, turbines, and various parts for wire extrusion types of equipment [9]. Additionally, these processes find application in hydraulic and pneumatic systems, oil well drilling equipment, and auxiliary components. The adoption of cost-effective metal products through RIC/RC processes can significantly reduce investment and production costs across various production ranges. Moreover, these processes offer a broad spectrum of raw materials, including metals, metal matrix composites, alloys, and superalloy, which expands avenues for further research and development.

Low-cost 3D Printing

Advanced metal 3D printing technologies such as Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Direct Metal Printing (DMP), Selective Laser Sintering (SLM), and Laser Powder Bed Fusion (LPBF)[10] utilize expensive energy sources like lasers and electron beams, along with costly metal powders, to produce exotic metal products. These technologies enable the creation of complex, free-form designs that are unachievable with traditional manufacturing methods. Industrial-grade metal 3D printers' prices range from several hundred thousand to a few million USD[11], while SLA or FDM 3D printers' prices typically range from a few hundred to a few thousand USD only. Shapes with lower to moderate complexity can be more cost-effectively produced through indirect or alternative methods such as Rapid Casting (RC). With the increasing popularity of low-cost 3D printing (3DP) technologies, Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF) and Stereolithography (SLA) have emerged as leading contenders. These technologies show promise for applications in polymer materials pattern-making for Rapid Casting (RC), facilitating the indirect production of metallic industrial products. Continuous research and development in technologies like Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF), and Stereolithography (SLA) for 3D printing is crucial to realize similar benefits in industrial applications.

As low-cost 3D printing (3DP) technologies gain popularity, Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF) and Stereolithography (SLA) have emerged as prominent choices. These technologies hold significant potential for use in pattern-making for Rapid Casting (RC), enabling the indirect production of metallic industrial products. The mesh or honeycomb building capability of FFF 3D printing provides sufficient material savings, especially under the surfaces of the

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workpiece. When used as a pattern in Rapid Casting (RC), it effectively accommodates thermal expansion during the ceramic mold burning process for cavity creation. In contrast, the SLA process is well-suited for producing non-engineering products such as jewellery and dental items dentistry [12–15], where stringent dimensional tolerances are not always required.

Improving dimensional accuracy in low-cost FFF and SLA processes through experimental investigation and utilizing these patterns in Rapid Casting (RC) could yield effective results for successful engineering implementation of this technology. This approach has the potential to substantially lower initial investment costs for manufacturing metallic products via the Rapid Casting route, which is beneficial for promoting entrepreneurship development and enhancing industrial applications.

Scopes in 3D Printing Towards Commercial Applications

3D printing, also known as additive manufacturing, encompasses a broad range of research areas, each crucial for advancing the technology and its applications. Printing; Process Optimization, aimed at refining printing techniques, speed, precision, and post-processing methods; and Applications and Innovations, which explore medical and bioprinting, aerospace and automotive applications, and construction. Additionally, Software and Design research involves advancements in CAD, modelling, simulation, testing, and topology optimization. Sustainability and Environmental Impact studies emphasize recycling, energy efficiency, and biodegradable materials. Quality Control and Metrology research focuses on inspection techniques and standardization, while Integration with Other Technologies explores the intersection of 3D printing with IoT, Industry 4.0, and hybrid manufacturing. Finally, Education and Skill Development initiatives aim to create training programs and foster collaboration across academia, industry, and government. These scopes highlight the diverse and interdisciplinary nature of 3D printing research, reflecting its potential to revolutionize various industries and drive technological advancements.

Challenges and Issues in 3D Printing For Commercialization

Several challenges in 3D printing, such as build size limitations, extended build times, and the need for precise dimensional accuracy and improved surface quality, are currently under active research and development. These challenges must be addressed for the successful mass commercialization of 3D printing technologies. Build size limitation remains a significant obstacle. While 3D printing can theoretically produce objects from nano to macro sizes, practical limitations persist, particularly in achieving larger build sizes. The slow deposition process, where units are built layer by layer, contributes to extended production times. Efforts are ongoing to enhance the efficiency and speed of this process to meet commercial demands effectively.

Research Progress On Dimensional Tolerances And Surface Accuracy

Cumulative dimensional errors in layer deposition may arise from factors such as voxel/unit deposition volumetric inaccuracies, material shrinkage effects, machine positioning errors caused by backlash, and temperature variations. Additionally, stair-stepping effects and surface roughness can contribute to dimensional inaccuracies to some extent.

Oluwole K. Bowoto et. al 2023[16] developed and applied a novel software algorithm to address dimensional variations in 3D printed models produced by extrusion techniques. Unlike traditional methods such as coordinate measuring machines, laser scanning, optical profilometry, and CT scanning, this algorithm leverages computer vision, offering a cost-effective alternative for assessing dimensional deviations. The software employs a three-step methodology-preparation, measurement, and analysis to evaluate both the CAD and G-code-sliced models, enabling real-time monitoring of dimensional variances during printing. Thoroughly tested across diverse geometries, the algorithm predicts potential print failures, enhancing the efficiency and resource management in additive manufacturing. The study concludes that the choice of assessment method should be tailored to the specific part type and accuracy requirements.

In 2023, Philip Nguyen et al. [17] examined the dimensional accuracy of vascular anatomical models created for each patient utilizing PolyJet 3D printing, Stereolithography (SLA), Fused-Deposition Modelling (FDM), and Selective Laser Sintering (SLS). Despite potential inaccuracies introduced during digital anatomical segmentation and processing, all printing methods produced high-quality models. Dimensional errors were minimal, with SLA, FDM, SLS, and Poly-Jet models showing overall errors of $0.20 \pm 3.23\%$, $0.53 \pm 3.16\%$, $-0.11 \pm 2.81\%$, and $-0.72 \pm 2.72\%$, respectively, compared to original CT angiograms. The models exhibited high dimensional accuracy, indicating their suitability for use as medical devices in clinical applications, thereby enhancing patient consultation, surgical planning, and training.

Raphaël Côté et al. 2023[18] introduced an overlapping strategy to enhance the dimensional accuracy and eliminate interbead defects in material extrusion 3D printing (MEX) of highly filled polymers. Traditional methods, such as over-extrusion, often compromise the dimensions of printed parts. By using a feedstock composed of SS powder and a wax-based binder, hollow square prisms were printed with varying overlapping ratios and layer heights. Key findings include that even a minimal overlap of 5% effectively reduced interlayer voids typically mitigated by reducing layer height.

Optimal overlap ratios between 15% and 20% eliminated rhomboid voids and minimized dimensional deviations.

However, overlaps greater than 25% introduced macroscopic defects, reducing part quality. This approach demonstrates significant potential for producing full-density, dimensionally accurate green parts in MEX.

Imanian and Biglari 2022 [19] explored the optimization of surface roughness and dimensional accuracy in Selective Laser Sintering (SLS) 3D printing of a polyvinyl alcohol (PVA) and carbon black (CB) composite. By employing a Central Composite Design (CCD), the research model affects key process variables laser power, laser speed, scan spacing, and layer thickness on these critical quality metrics. Using a custom-built desktop SLS printer, the study demonstrates that precise control of these variables can significantly improve print quality. Specifically, reducing laser speed, layer thickness, and scan spacing lowers surface roughness, while decreasing laser power has the opposite effect. The study also highlights the importance of understanding the nonlinear interactions between variables, which are illustrated through energy density plots. The developed mathematical models, verified through analysis of variance, provide a robust framework for predicting and optimizing dimensional accuracy and surface roughness in SLS 3D printing, advancing the practical application of new composite materials in this technology.

Novelty of The Present Work

B. Haldar 2023[20] introduced a simple mathematical model for CAD solid model tuning to improve the dimensional accuracy of 3D printed objects printed by low-cost 3D printers, providing experimental proof primarily for external dimensions. In this work, the author extends the investigation by experimentally validating the proposed CAD solid model tuning method for both external and internal dimensions, thereby offering a more comprehensive assessment of the method's effectiveness.

Research Objectives

This research aims to investigate the feasibility of using cost-effective 3D printers for engineering product manufacturing, employing a novel solid model tuning approach integrated into Rapid Casting (RC). Objectives include developing and refining solid models using Fused Filament Fabrication (FFF) and Stereolithography (SLA) technologies to enhance external and internal dimensional accuracy in X, Y, and Z directions, and evaluating their suitability as patterns for metallic part production via 3D printing and Rapid Casting processes.

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MATERIALS AND METHODS

3DP Machine and Material Details

In this investigation, budget-friendly Digital Light Processing (DLP) and Fused Filament Fabrication (FFF) 3D printing machines are utilized. A solid model shown in Fig. 1 is utilized for X, Y, and Z directions dimensional internal and external error study after fast time specimen 3D printing and error tuning. Details regarding the machines and materials are as follows:

The SLA 3D printer used in this investigation is the JX215 (Fig. 2 (a)), manufactured in China. It operates on DLP (Digital Light Processing) technology with a light-curing LCD, offering a build volume of (215×135×150) mm³ per hour. The LCD screen spot size is 0.0067 mm², utilizing 405 nm wavelength light for curing photopolymer resin. The printer achieves a layer thickness of 0.025 mm, and it comes equipped with Slicer 2.4.0 software to generate STL files from AutoCAD 3D models.

The FFF 3D printer used is the Ultimaker S3 (Figure 3(a), manufactured in the USA. It features a build size of (230×190×200) mm³, with a printing speed of approximately 24 mm³/s. The printer is equipped with a 0.25 mm nozzle and operates with PLA filament, maintaining a nozzle temperature of 220°C for printing. The 3D-printed real work specimens are shown in Figure 2 (b) and 3 (b).

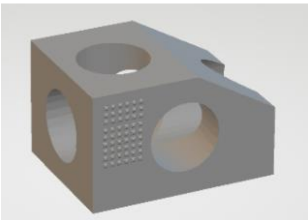

Figure 1. The STL 3D model used in the study for error tuning.

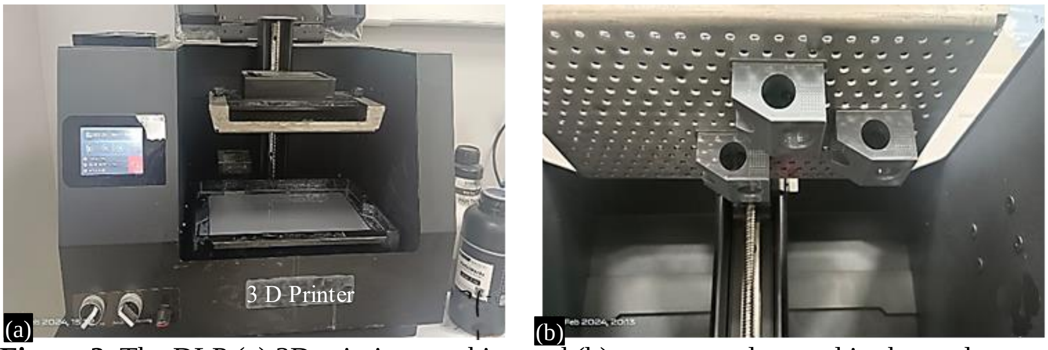

Figure 2. The DLP (a) 3D printing machine and (b) some samples used in the study.

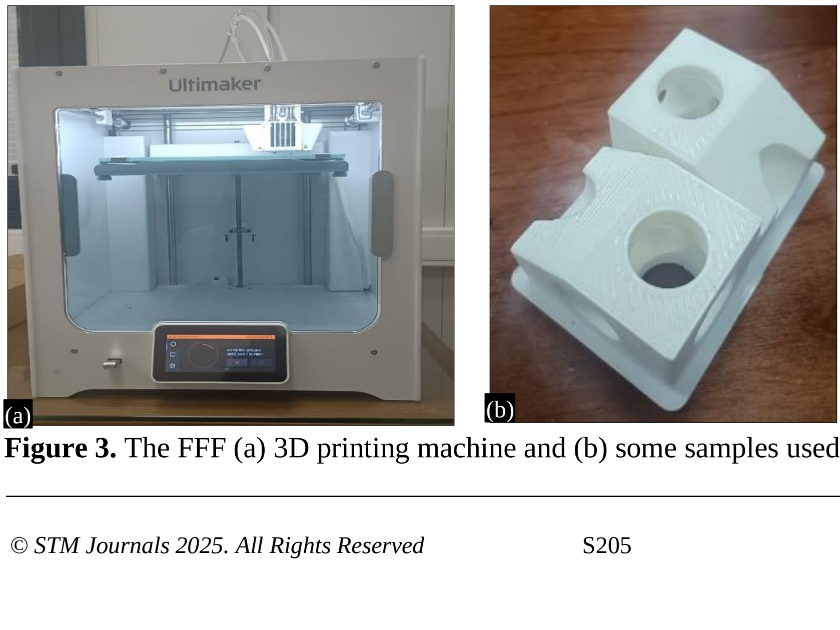

Figure 3. The FFF (a) 3D printing machine and (b) some samples used in the study.

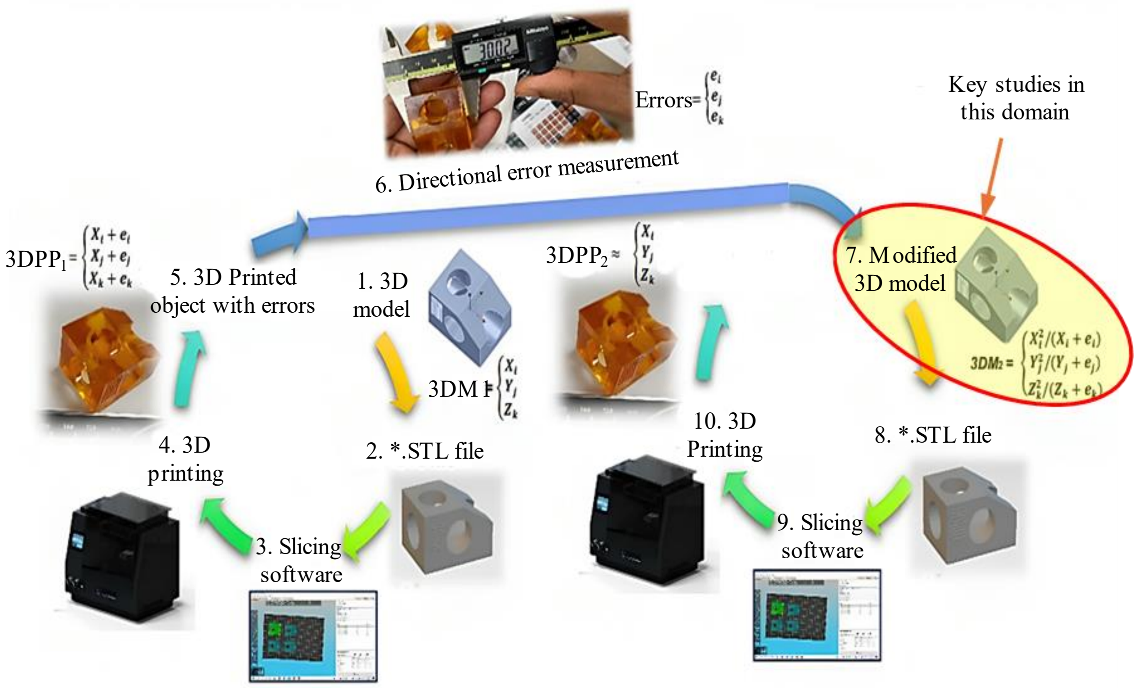

Figure 4. Solid model tuning process cycle for error compensation in dimensional accuracy improvement[20] and the highlighted area of the present study.

Method for CAD Solid Model Tuning

The technique and experimental process for tuning solid model dimensions are detailed in Figure 4, illustrating the process flow cycle. All dimension measurements represent the average of three consecutive readings to ensure accuracy and reliability.

The Error-Tuning Model For External and Internal Dimensional Improvement

The model [20] for calculating dimensional errors when tuning a 3D model to achieve the target dimensions in 3D printed parts is as follows:

$\begin{cases} X_i \\ Y_j \\ Z_k \end{cases} \rightarrow$	$\begin{cases} X_i^2/(X_i + e_i) \\ Y_j^2/(Y_j + e_j) \\ Z_k^2/(Z_k + e_k) \end{cases}$
Final product dimensions	*Tuned 3D model dimensions* [20]

Where, X_i, Y_j, *and* Z_k are the actual 3D model dimensions and e_i, e_j, and e_k ; are the measured errors on 3D printed parts in *X*, *Y*, and *Z* directions, respectively.

3D model tuning can be performed using two primary approaches: employing established 3D modelling software (e.g., AutoCAD, SolidWorks) and utilizing the slicing software integrated with the 3D printer. For models exhibiting uniform dimensional errors, adjustments can be effectively made through the slicing software. Conversely, when errors are anisotropic, precise tuning must be conducted within the base 3D model using solid modelling software. In such scenarios, internal features may require redrawing to conform to the recalibrated dimensions. This work provides a detailed step-wise error adjustment in 3D model depiction of the tuning process for both internal and external features, as illustrated in Figure. 5, addressing aspects not covered in the innovator studies.

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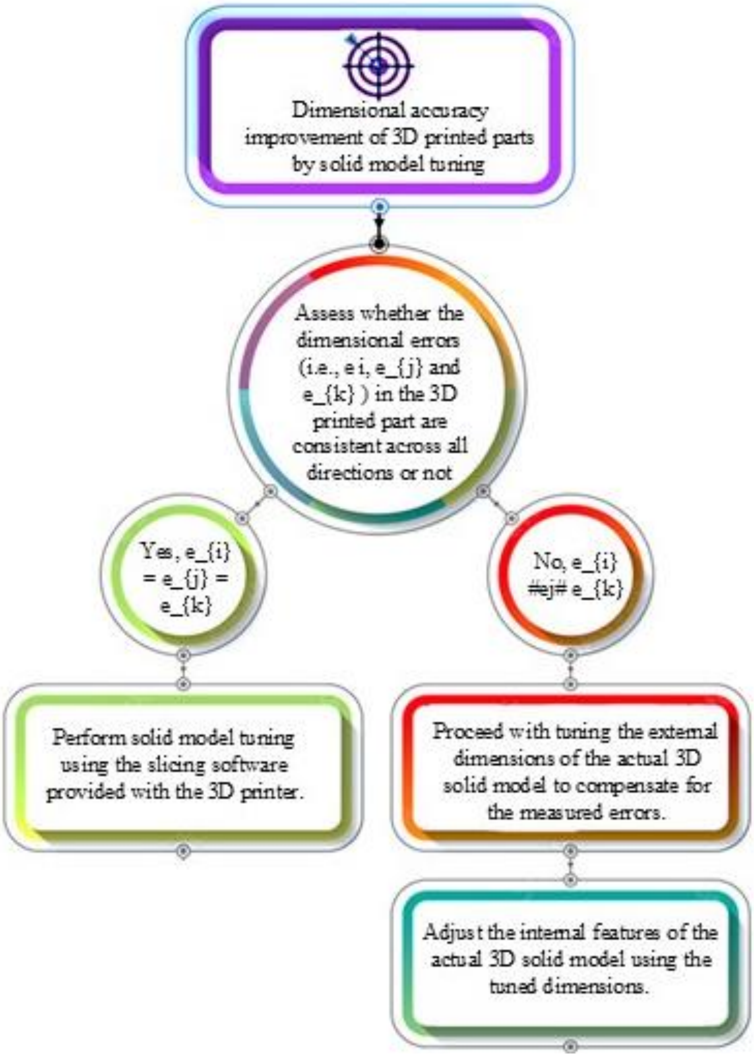


Figure 5. Internal and external dimension tuning process in 3D solid model.

Table 1. Dimensional error measuring process.

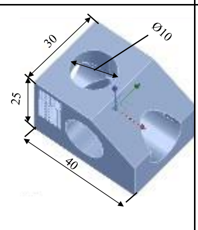
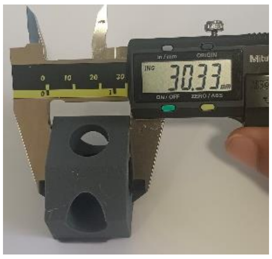
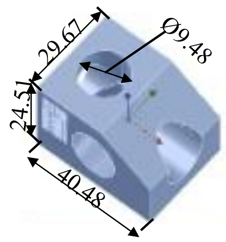
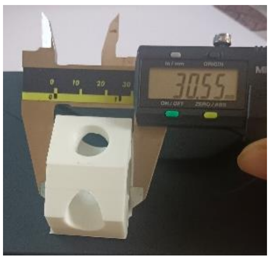
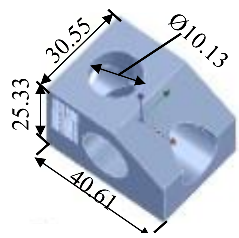
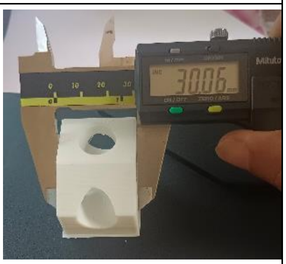
3DP process	3D Solid model	1st 3D printed object (3DM1)	Tuned 3D model	Modified 3D printed object (3DM2)
SLA				
FFF				

Table 2. The measured 3D printed parts dimensions before and after 3D printing and tuning

Dimension type		3D object directions	3D Solid model (actual target) (mm)	1st 3D printed object ($3DM_1$) (mm)	Tuned 3D model (mm)	Modified 3D printed object ($3DM_2$) (mm)	Actual Error (%) in ($3DM_1$) (Before tuning)	Error (%) in 3D printed specimen after tuning ($3DM_2$)	Reduction in IErrorI (%) after first validation
SLA	External	X	40	40.48	39.53	40.05	1.20%	0.12%	1.08%
		Y	30	30.33	29.67	30.01	1.10%	0.03%	1.07%
		Z	25	24.51	25.50	25.03	-1.96%	0.12%	2.08%
	Internal (hole)	X	10	9.48	10.55	9.97	-5.20%	-0.30%	4.90%
		Y	10	10.12	9.88	10.04	1.20%	0.40%	0.80%
		Z	10	9.38	10.66	9.96	-6.20%	-0.40%	5.80%
FFF	External	X	40	40.61	39.40	40.06	1.53%	0.15%	1.37%
		Y	30	30.55	29.46	30.06	1.83%	0.20%	1.63%
		Z	25	25.33	24.67	25.02	1.32%	0.08%	1.24%
	Internal (hole)	X	10	10.13	9.87	10.08	1.30%	0.80%	0.50%
		Y	10	10.12	9.88	10.11	1.20%	1.10%	0.10%
		Z	10	10.11	9.89	10.09	1.10%	0.90%	0.20%

The experiments are conducted on 3D-printed parts, with both internal and external dimensions being evaluated. The dimensional errors were not uniform in all directions, so the solid model was adjusted based on (No, $e_i \# e_j \# e_k$) the actual 3D model. A 3D solid CAD model with external dimensions of (40 mm×30 mm×25 mm) with internal holes of 10 mm is used for both SLA and FFF 3D printed parts ($3DM_1$), and the modified/tuned 3D CAD model with improved 3D printed parts as shown in Table 1.

RESULTS AND DISCUSSION

For model validation, the external and internal dimensions of 3D printed parts are measured before and after tuning the 3D model (as described in Table 1). The improvement in dimensional accuracy is presented in Table 2.

By applying the referred mathematical model[20], the internal and external dimensional accuracy of 3D-printed parts significantly improved, as obtained in Table 1. Dimensional errors were reduced by up to 5.80% in internal hole diameters and up to 2.08% in external dimensions. The model effectively reduced external dimensional errors, with positive errors in $3DM_2$ indicating that closer tolerances can be achieved after post-processing. While similar improvements were achieved for internal hole diameters, the negative errors in $3DM_2$ are acceptable since the hole diameter can be increased during post-processing. Thus, the dimensional accuracy could be greatly enhanced using this error-tuning model, where positive errors in external dimensions and negative errors in internal dimensions are essential for acceptable engineering applications. For internal errors (with negative signs) within acceptable limits, further trial and error corrections may be necessary to achieve tighter tolerances with negative zones.

CONCLUSION

To validate the solid model tuning technique for increasing internal and external dimensional accuracy and to apply it to engineering and industrial applications, this study's experimental investigation was carried out. The following observations result from this work:

- The solid model tuning technique is effective for improving both internal and external dimensional accuracy of end products.
- For acceptable tuned dimensions in end parts, positive errors in external dimensions and negative errors in internal dimensions are preferred for engineering applications.

- Cost-effective 3D printing technologies, such as FFF, DLP, etc. can be used for economical engineering applications and metal product manufacturing via the Rapid casting (RC)/Rapid investment casting(RIC) route in job shop to batch production, utilizing solid model tuning.
- Designed engineering products are considered acceptable if they fall within the specified tolerance limits. Therefore, tuning CAD solid models can enhance the acceptability of 3D-printed products by improving their dimensional accuracy within these limits. The experimentally validated mathematical model tuning method can also be applied to other 3D printing techniques to further enhance dimensional accuracy, ensure compliance with engineering tolerances, and promote sustainability across a wide range of applications, including automotive, aerospace, medical and dental fields, molds and tooling, jewelry and luxury goods, reverse engineering, mass customization, robotics, defense, firearms, and more.

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