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Analysis of additive manufacturing errors under different conditions

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ABSTRACT: *Additive manufacturing is becoming an increasingly valuable tool in engineering practice, finding applications not only in prototyping but also in creating fully functional parts for real-world applications. This rapid adoption highlights the importance of understanding the properties and parameters of the parts being manufactured to ensure their performance and reliability. Among these parameters, the accuracy of the manufactured parts plays a crucial role, directly affecting their fit, functionality, and overall quality.*
This article focuses on the accuracy of components manufactured using the additive manufacturing technology Fused Deposition Modeling (FDM). The study examines how various 3D printer settings, such as layer height, print speed, and nozzle temperature, affect the dimensional accuracy of the final product. It also examines how the orientation of the part during the printing process affects the overall accuracy and consistency. By analyzing these factors, this article aims to provide an overview of optimizing FDM processes to achieve better accuracy and increase the applicability of additive manufacturing in various industries.

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I. INTRODUCTION

Additive manufacturing, commonly referred to as 3D printing, has revolutionized the way products are designed and manufactured across a wide range of industries. Unlike traditional subtractive manufacturing methods, where material is removed to create a part, additive manufacturing builds objects layer by layer using digital models. This innovative approach allows for unprecedented design flexibility, material efficiency, and customization, making it ideal for both prototyping and manufacturing functional components. Among the various additive manufacturing techniques available, Fused Deposition Modeling (FDM) is one of the most widely used, due to its affordability, accessibility, and versatility.[1]

Despite its many advantages, the practical application of FDM technology is not without its challenges. One of the most important aspects of this process is ensuring the dimensional accuracy of the parts produced. Accuracy is essential for components that must meet strict design specifications or fit into larger assemblies. Even small deviations from the intended dimensions can lead to misalignment, mechanical failure, or reduced functionality, especially in applications requiring high precision, such as aerospace, automotive, and medical industries.[2].

The accuracy of FDM-produced parts is affected by many factors, including 3D printer settings, material properties, and part orientation during the printing process. For example, parameters such as layer height, print speed, extrusion temperature, and cooling conditions significantly affect the final quality of the part. Similarly, the orientation of the part on the print bed can lead to variations in surface finish, dimensional accuracy, and mechanical strength due to the anisotropic nature of the printed layers.[3]

Understanding these variables and their impact on the accuracy of FDM-produced parts is critical for optimizing the process and achieving consistent, high-quality results. While additive manufacturing has been extensively studied, the interplay between printer settings, part orientation, and resulting accuracy remains an area of active research and practical importance. Addressing these challenges not only improves the reliability of the manufacturing process, but also expands the range of applications in which FDM can be effectively utilized.[4]

This article examines the factors affecting the accuracy of parts produced by FDM, with a particular focus on the role of printer setup and part orientation. By examining these aspects, the study aims to provide valuable insights for engineers and manufacturers seeking to optimize their processes and achieve greater accuracy in additive manufacturing.

The accuracy of parts produced by 3D printing depends on several factors, including the type of 3D printing technology, the overall quality of the printer, the material being used, and the level of calibration and maintenance of the 3D printer. Below is a breakdown of these factors and how they influence the precision of printed parts[7]:

1. 3D Printing Technology[5]**:**
- Fused Deposition Modeling (FDM): This is the most commonly used technology in consumer-grade 3D printers. It provides moderate accuracy with visible layer lines. The typical dimensional accuracy is ±0.5 mm, making it suitable for simple prototypes and non-functional parts. However, the surface finish and precision may not meet the requirements of high-end applications.[6]
- Stereolithography (SLA): Known for its high accuracy and smooth surface finish, SLA uses a fine laser beam to cure liquid resin into solid layers. It can produce layers as thin as 25 microns with a dimensional accuracy of ±0.1 mm, making it ideal for highly detailed and precise components.
- Selective Laser Sintering (SLS): This method offers good dimensional accuracy without the need for support material, significantly reducing post-processing times. With a typical accuracy of ±0.1 mm, SLS is well-suited for complex geometries and functional prototypes.
- Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM): These metal-based printing technologies provide the highest accuracy among 3D printing methods, with tolerances of ±0.05 mm depending on the material used. They are widely applied in the aerospace, automotive, and medical industries, where precision and material strength are critical.

2. Printer Calibration and Maintenance
Proper calibration and regular maintenance are essential for achieving consistent accuracy in 3D printing. This includes:
- Adjusting the nozzle temperature, extrusion rate, and bed level to ensure optimal material flow.
- Calibrating the Z-axis, belts, and screws to prevent misalignment, wear, and slippage.
- Addressing printer fatigue and mechanical wear to avoid layer deviations that could compromise the dimensional accuracy.

Failure to maintain these parameters can lead to inaccuracies, such as incorrect layer deposition or dimensional misalignment, which can negatively affect the final part.

3. Material Properties
The properties of the material used in 3D printing significantly influence the accuracy of the final part. For instance:
- ABS plastic tends to warp more than PLA during cooling, leading to dimensional inaccuracies.
- Materials explicitly designed for 3D printing, such as composite filaments or high-performance resins, often exhibit better stability and less shrinkage.

Adjusting print settings, such as temperature and cooling rate, can help mitigate issues like warping or shrinkage, ensuring better dimensional consistency.

4. Print Settings
Print settings, including layer height, print speed, infill density, and shell thickness, directly affect accuracy and part quality:
- Layer Height: Thinner layers improve surface smoothness and accuracy but increase print time.
- Print Speed: Faster speeds may result in vibrations and less precise movements, reducing accuracy.
- Shell Thickness and Infill Density: Thicker shells and higher infill densities enhance strength but may cause internal stress, potentially warping the part. Careful balancing of these parameters is essential to achieve the desired accuracy and performance.

5. Post-Processing
Post-processing techniques such as sanding, milling, or polishing can enhance the accuracy and surface finish of 3D-printed parts. While these methods improve tolerances and aesthetics, they must be applied carefully to avoid altering critical dimensions or compromising the functionality of the part.[3]

II. EXPERIMENTAL SECTION

The prototype of the experiment was created using SolidWorks software, while PrusaSlicer was used to generate g-codes and edit orientations. SolidWorks is a mechanical design automation tool that allows designers to quickly conceptualize ideas, allowing them to experiment with different features and dimensions. The software can quickly create models and detailed drawings based on the parameters and features defined in solid modeling. SolidWorks offers three main modes: part mode, assembly mode, and drawing mode. Part mode is the basic component of the software where individual parts are created. Before an assembly can be built, the designer must first create parts. Assembly mode allows the integration of individual components or other assemblies (known as subassemblies) to create a complete design. Drawing mode is the mode where detailed technical drawings are created based on the models.

SolidWorks also includes simulation capabilities, making it user-friendly for designers. It offers multiple options for running studies under different conditions and material properties, helping to analyze and optimize designs. Developed by Prusa Research, PrusaSlicer is a powerful and versatile 3D slicing software. Based on the open source Slic3r project, it has been heavily customized and enhanced by Prusa Research to support their own 3D printers as well as a variety of other models from different manufacturers. This software is essential for preparing models for 3D printing, offering precise control over print settings and ensuring optimal print results.

The experiment was conducted using five different angles of printing the sample to test the dimensional accuracy of the printer under different conditions, using two printers of similar model. A sample was designed to print, which contains combinations of circles and rectangles, as shown below. Measurements were taken on these prints using a digital caliper to assess the accuracy and consistency of the printed dimensions.

Each print was carefully examined to determine any variations in size or shape that may result from different print angles, helping to evaluate how the printer's performance is influenced by orientation. The use of two similar printers allowed for a comparison of results, ensuring the reliability of the findings.

The sample was designed with 2 hollow circles- inner diameter, 2 circles – outer diameter, 2 hollow rectangles- inner length*breadth,2 rectangles-outer length*breadth of different dimensions were considered for the calculations.

The different print angle orientations used for the experiment are

Flat on face – F
90* VERTICAL – V90
90*HORIZONTAL – H90
45*VERTICAL – V45
45*HORIZONTAL – H45

The experiment was conducted using Prusa MKS 3 – 3D printer with the below specifications;

Filament – PLA -1.75mm
Filament extruder diameter – 0.4mm
Extrusion temperature – 215*C, Bed temperature – 60*C
Infill – Rectilinear pattern-15%
Speed -80mm/s

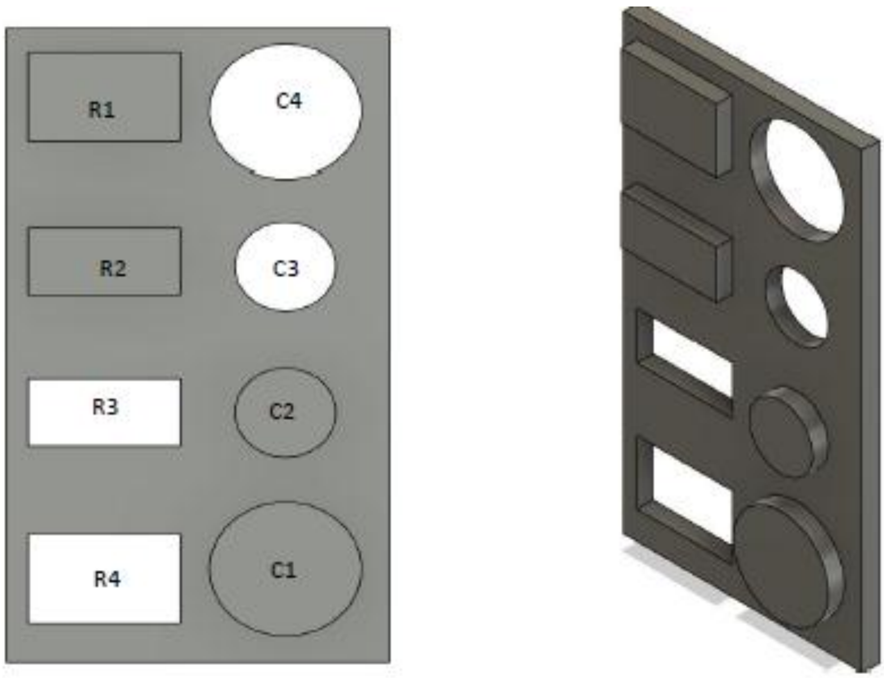

Fig - 1: Design of experimental sample

	CIRCLE				RECTANGLE							
DIMENSIONS	30	20	20	30	20	30	15	30	15	30	20	30
	C1 OUT	C2 OUT	C3 IN	C4 IN	R1 OUT 20*30		R2-out 15*30		R3 inner 15*30		R4 inner 20*30	
F	29.88	19.932	19.752	29.81	19.965	29.937	14.973	29.953	14.936	29.907	19.86	29.901
V90	30.043	20.039	19.858	29.921	20.079	30.25	15.032	29.992	14.91	29.951	19.839	29.954
H90	30.02	19.9478	19.958	29.928	19.973	30.223	14.982	30.19	15.021	29.844	20.022	29.791
V45	29.899	19.956	19.886	29.953	20.028	29.903	15.069	29.905	14.92	29.92	19.8044	29.891
H45	29.929	19.914	19.925	29.791	19.945	29.835	14.984	29.989	14.926	29.848	19.833	29.77
AVERAGE	29.9542	19.9578	19.8758	29.8806	19.998	30.0296	15.008	30.0058	14.9426	29.894	19.87168	29.8614

Fig - 2: Combined measured data

	Error in F	Error in V90	Error in H90	Error in V45	Error in H45
C1 OUT 30	0.40%	0.14%	0.07%	0.34%	0.24%
C2 OUT 20	0.34%	0.20%	0.26%	0.22%	0.43%
C3 IN 20	1.24%	0.71%	0.21%	0.57%	0.38%
C4 IN 30	0.63%	0.83%	0.74%	0.16%	0.55%
R1 OUT 20x30	0.18%	0.40%	0.14%	0.14%	0.28%
R2 OUT 15x30	0.21%	0.83%	0.74%	0.16%	0.55%
R3 IN 15x30	0.18%	0.21%	0.12%	0.46%	0.11%
R4 IN 20x30	0.70%	0.81%	0.11%	0.98%	0.84%

Fig - 3: Percentage error of the samples

III. CONCLUSION

Based on the above measurements, we can conclude the following ranking of printing angles from best to worst in terms of dimensional accuracy:

- V90 (vertical 90 degrees): This angle exhibits the least variance, making it the most accurate and closest to the expected results. This means that the 3D printer works best when printing vertically upwards at a 90-degree angle, which ensures the highest level of dimensional accuracy.

- H90 (horizontal 90 degrees): This angle also exhibits the least variance, making it almost as reliable as V90 in maintaining correct dimensions. Printing along a horizontal line at a 90-degree angle offers high dimensional accuracy, with the printer performing almost as well as in a vertical orientation.

- V45 (vertical 45 degrees): Printing at this angle shows significant deviation, meaning it is not as reliable as V90 or H90, but still provides better results than other angles. This indicates that printing at a 45-degree vertical angle results in moderate dimensional accuracy, although it may result in slight inconsistencies compared to 90-degree angles.

- H45 (horizontal 45 degrees): This angle exhibits larger deviations than V90, H90, and V45, indicating a decrease in reliability. Printing at a horizontal 45-degree angle may result in greater inconsistency in printed dimensions, and therefore may not be the optimal choice for high-precision prints.

- F (Flat): Printing flat results in the largest deviation, making it the least reliable angle. This means that printing at a flat angle results in significant errors or deviations in expected dimensions, indicating that this is the most inconsistent print orientation.

The experiment revealed that printing samples at 90-degree angles, either vertically or horizontally, resulted in better dimensional accuracy. Changes to printer settings did not significantly affect overall dimensions. Based on the data, the following recommendations can be made for optimal printing conditions:

For the best dimensional accuracy, print at 90-degree angles, either vertically or horizontally.
Avoid using flat or 45-degree angles for prints requiring high precision, as they tend to create larger deviations.
Consider the specific requirements of your project when choosing print angles, balancing print time, and quality.
This knowledge can help improve the overall performance and consistency of your 3D printing process.

Design Recommendations

- 3D printing should be designed with the printing process in mind, ideally at component design time. Critical features should be oriented in either the V90 or H90 position to achieve the best dimensional accuracy.
- Tolerances should be included in the design of components that are particularly challenging to manufacture. In cases where printing at non-optimal angles is unavoidable, these tolerances will help account for potential printing errors and dimensional variations.

3D Printer Calibration

- A 3D printer should be calibrated at regular intervals to ensure consistent performance. Adjustments to settings that affect print angles are crucial as they will affect the dimensional accuracy of the print.
- It is essential to regularly test the printer's performance when printing from different angles. If deviations are found, further adjustments should be made to improve performance. A combination of optimal print angles should be selected and this information should be clearly documented in the user manual.

Steps to Improve Accuracy

- Use V90 and H90 orientations for critical and dimensionally sensitive parts to ensure the highest level of accuracy.
- Avoid using F (flat) orientation for parts that require high accuracy, as it is prone to the largest deviations.
- Design parts in a way that supports optimal orientation for printing, favoring V90 and H90 whenever possible. Calibrate and test your printer regularly to ensure consistent performance at all angles.

Implementing these design and calibration practices can significantly improve the overall accuracy and reliability of your 3D printed components and ensure they meet the required specifications.

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