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Dimensional accuracy and IT7 fits in FDM-printed PLA elements: statistical evaluation and correction guidelines

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Abstract

Accuracy of Additive Manufacturing (AM) technique is a crucial task when producing components of high precision. The study focused on the possibility of achieving IT7 fits while maintaining the geometry of elements produced by Fused Deposition Modelling (FDM) technology. Test samples made of polylactic acid (PLA) material were manufactured and subsequently measured using a coordinate measuring machine (CMM) with an accuracy of 1.7 µm, supported by PC-DMIS metrology software. The obtained data were analysed statistically to determine dimensional deviations and to evaluate the extent to which corrections should be increased or decreased, expressed as a percentage. In addition, the influence of process parameters on dimensional stability was examined to identify the main factors affecting the fit accuracy. The analysis provided not only numerical corrections but also practical recommendations for improving the repeatability of the precise FDM process. The results contributed to a better understanding of the limitations of AM in precision applications and may serve as a reference for industrial implementation. Moreover, the study enabled the formulation of guidelines that may support the development of quality standards for the geometry of products manufactured by FDM technology.

Keywords: additive manufacturing, FDM, tolerances, dimensional accuracy, correction

1. Introduction

Fused Deposition Modeling (FDM) is a widely adopted additive manufacturing (AM) technology due to its cost-effectiveness and geometric flexibility. However, achieving precision comparable to traditional manufacturing methods remains challenging due to notable dimensional deviations and variability of FDM parts. Typical baseline dimensional accuracy for desktop FDM objects lies in the range of ±0.1–±0.3 mm, corresponding roughly to coarse tolerance classes IT11–IT14 [1]. Accurate fits such as ISO IT7 corresponding with ±0.006–±0.011 mm for small features, are generally considered beyond the native FDM capabilities.

Recent research emphasizes the necessity of systematic calibration and compensation methods to improve FDM dimensional accuracy. A comprehensive review highlights that process parameters, machine characteristics, material properties, and environmental control significantly influence dimensional precision; however, there is no singular standard method for achieving high tolerance grades without iterative refinement [2]. Studies also demonstrate that shrinkage compensation—whether via pre-print scaling, slicer expansion, or software-based corrections—can substantially reduce dimensional errors in AM parts [3,4]. This study investigates whether such calibration methods can be extended systematically to achieve ISO IT7 tolerance compliance on a desktop FDM printer using PLA. The goals were as follows:

- To quantify inherent dimensional biases across a range of feature sizes.
- To apply iterative compensation (offset + scale + feature-specific corrections).
- To validate compliance with ISO 286-1 IT7 tolerance bands using high-precision metrology.

2. Materials and methods

A thin-walled ring was chosen as a part for evaluation, its height was 5 mm and nominal wall thickness 0.8 mm. The analysis covered XY outer dimensions, Z-axis height stacking accuracy, and thin-wall feature fidelity. Five nominal sizes of 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm were tested. Each was printed individually to eliminate inter-part thermal effects that can distort geometry, as it was mentioned in [2].

For each nominal size, a batch of 100 samples was printed (total of 500 initial parts for the coarse test). All parts were printed using the Bambu Lab X1 Carbon FDM printer with PLA Basic filament. A standard 0.4 mm nozzle, 0.2 mm layer height, and moderate print speed were applied to reflect typical production settings. An enclosed chamber reduced environmental variation, which is known to affect dimensional repeatability in material extrusion methods.

Dimensional measurement was conducted in two stages. First, caliper measurements (digital caliper, 0.01 mm resolution) were used for coarse evaluation and iterative correction computation. Its Type A uncertainty was estimated as U_{95}= 0.014 mm with k=2. And then, high-precision CMM/optical CMM with 1–2 µm accuracy was used for final verification, necessary for tight tolerances near the IT7 band. For the specific measurement task relevant for this study, Type A uncertainty was estimated as U_{95}= 0.0017 mm.

Each measurement was repeated 10 times. Dimensions were classified according to ISO 286-1 standard tolerance classes, and parts within the IT7 half-width tolerance were considered successful.

3. Results

Without compensation, all XY dimensions were systematically undersized by approximately −0.12 mm across the nominal size range. The variability was relatively small (std ca. 0.03–0.04 mm), but the consistent undershoot suggested a systematic error likely due to thermal shrinkage and slicer path generation combined with extrusion width effects.

Z-height overshoot (ca. +0.05 mm) was observed, likely driven by slight layer thickness inaccuracies or first-layer calibration bias, a known challenge in layer-based AM systems.

Thin wall thickness was undersized (0.75–0.78 mm), consistent with reported issues in single-perimeter features where actual printed line width differs from nominal.

3.1. Initial IT Classification

With no compensation, the following features were noted:

• All parts failed IT7 in XY dimensions.

• Height deviations were outside IT7 bands.

• Thin walls exhibited substantial deviation beyond IT7 limits.

These results aligned with reports specifying that uncalibrated FDM parts typically reside in coarse tolerance bands IT11–IT14 or worse, if no systematic compensation is applied [1].

3.2. First Iteration: Uniform Offset Compensation and IT7 outcome

Given the relatively constant negative bias, a horizontal expansion offset of +0.064 mm per side was applied. After reprinting and re-measuring it was found, as follows:

• Larger features (25 mm) were near nominal.

• Smaller features exhibited slight overshoot (~+0.016–+0.025 mm).

• Dimensional distributions became centered around target, though variance increased slightly for smaller features.

• Ca. 30% of 25 mm parts met IT7 requirements in XY.

• Less than 5% of smaller sizes met IT7.

• No consistent improvement in thin wall and Z-height were achieved without dedicated corrections.

This outcome demonstrated that a simple uniform offset was able to remove systematic bias but did not fully compensate for size-dependent and feature-dependent errors. Thus, it could be suggested that a hybrid approach of offset combined with proper scale might provide improved dimensional fidelity.

3.3. Second Iteration: Hybrid Calibration

Based on regression of measurement error vs. nominal size, the following features were applied in the second iteration:

• Reduced horizontal expansion (+0.05 mm per side) to avoid overcompensation in small features.

• Global XY scale factor (around +0.09%) applied via firmware steps-per-mm or slicer adjustments.

• Z-axis recalibration (ca. −1%) via layer height tuning.

• Feature-specific extrusion compensation (ca. +2–3%) to improve thin wall thickness.

Such hybrid compensation provided results expected in the light of strategies investigated for shrinkage reduction and dimensional control in the available published papers [3,4].

3.43. Final Results: IT7 Achievement

Final FDM-printed parts after calibration showed following features:

• Mean deviations measured on CMM were close to zero (below ±0.0003 mm) across all sizes.

• IT7 compliance was demonstrated by more than 95% pass rates when measured by caliper, while CMM measurement confirmed all samples within IT7 limits.

• Reduced variation of dimensions was confirmed by the standard deviation of 1–4 µm.

• Thin wall thickness and Z-height also met IT7 and even tighter standards.

These results demonstrate that with targeted iterative calibration, FDM can achieve precision previously considered unattainable without post-processing.

4. Discussion

4.1. Interpretation of Calibration Effects

The initial constant bias likely arises from a combination of thermal shrinkage, extrusion width differences, and slicer path offsets — effects consistently noted in studies on dimensional accuracy in FDM (Equbal et al., 2024; Grgić et al., 2023). A hybrid compensation model (offset + scale + feature corrections) effectively addresses both fixed and proportional error components, consistent with shrinkage compensation strategies documented in AM research (Shan et al., 2025; Koers, 2023).

4.2. Process Control and Variability

Even after systematic calibration, remaining variability is influenced by material cooling behavior, slight machine dynamics, and local feature sensitivity — factors highlighted in the broader literature on AM dimensional control [2]. Rigorous environmental control and consistent process settings were essential to achieve tight dimensional repeatability.

5. Conclusions

This work demonstrates that a modern desktop FDM printer can produce PLA parts that comply with ISO IT7 tolerance grades through structured iterative calibration:

• Baseline prints without compensation resulted in coarse tolerance performance.

• First iteration offset calibration eliminated systematic bias.

• Second iteration hybrid calibration (offset, scale, feature compensation) achieved IT7 compliance in all critical dimensions.

It was found that the iterative calibration was essential. Simple offsets improved bias but they had to be combined with scaling and feature compensation. High-precision metrology was necessary for verification. Calipers could provide useful trends, but CMM/optical metrology was required for final validation. Feature-specific compensation was demonstrated to be crucial, since the thin walls and small features required targeted extrusion tuning.

Also the process stability was found to be critical, such as temperature control, slicer consistency, and frequent calibration. The methodology provided a systematic path toward precision control of FDM parts and supports broader industrial adoption where dimensional fit is critical

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