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INVESTIGATING LESS-EXPLORED FACTORS INFLUENCING ACCURACY IN MEX AND MSLA ADDITIVE MANUFACTURING PROCESSES

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This study was focused on investigating the dimensional accuracy of parts produced by two low-cost additive manufacturing processes, namely Masked Stereolithography (MSLA) and Material Extrusion (MEX). The analyzed factors were filament moisture, belt tension, build orientation, exposure time, and lift speed. A benchmark was 3D-printed under controlled conditions, and deviations from the nominal part were measured using 3D scanning. Main findings showed that filament dehydration improved MEX accuracy, with RMS errors reduced to 0.115 mm, while belt tension influenced consistency depending on filament condition and orientation. In MSLA, lower exposure times (2.5 s) and standard lift speeds (600 mm/min) reduced overcuring effects, producing RMS values as low as 0.139 mm. Overall, MEX achieved lower deviations than MSLA among the analyzed parameter sets, highlighting the importance of proper material handling and 3D printer mechanical tuning.

Keywords: 3D printing, accuracy, belt tension, moisture, lift speed, exposure time, build orientation, Material Extrusion, Masked Stereolithography, 3D scanning

1. Introduction

The capability of a manufacturing process to produce accurate parts is one key indicator of its development and maturity level, and, as all the other technologies, Additive Manufacturing (AM) is also assessed from this standpoint in order to ensure that its equipment can produce parts that meet the expected requirements [1-2]. For low-cost 3D printers such as those based on vat photopolymerization with Masked stereolithography (MSLA) and Material Extrusion (MEX), the evaluation of the 3D printing accuracy is important given their widespread use in prototyping, education, and functional applications [3]. This is necessary not only to validate these processes' applicability, but also to avoid the perception that these systems lack precision, as their performance can be enhanced through proper calibration, material handling, and parameter optimization [4-5].

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The factors influencing the accuracy in AM can be grouped into four main categories: material-related (e.g., filament moisture content, filler type and distribution in MEX; resin viscosity and photoinitiator concentration in MSLA), hardware-related (e.g., backlash and belt tension in MEX; projector resolution and Z-axis stability in MSLA), process parameter-related (e.g., extrusion flow rate and retraction distance in MEX; exposure time and layer thickness in MSLA), and printing condition-related (e.g., build orientation and environment temperature for both processes, platform adhesion and cooling efficiency in MEX; resin temperature and light scattering in MSLA). The systematic investigation of these factors and of their contribution to the prints' accuracy allows not only to improve the outcomes, but also to increase user confidence in affordable AM processes. Thus, recent studies showed that if properly calibrated and with process parameters optimized for the targeted application and material, low-cost 3D printers can achieve accuracy levels suitable for practical applications [6-8].

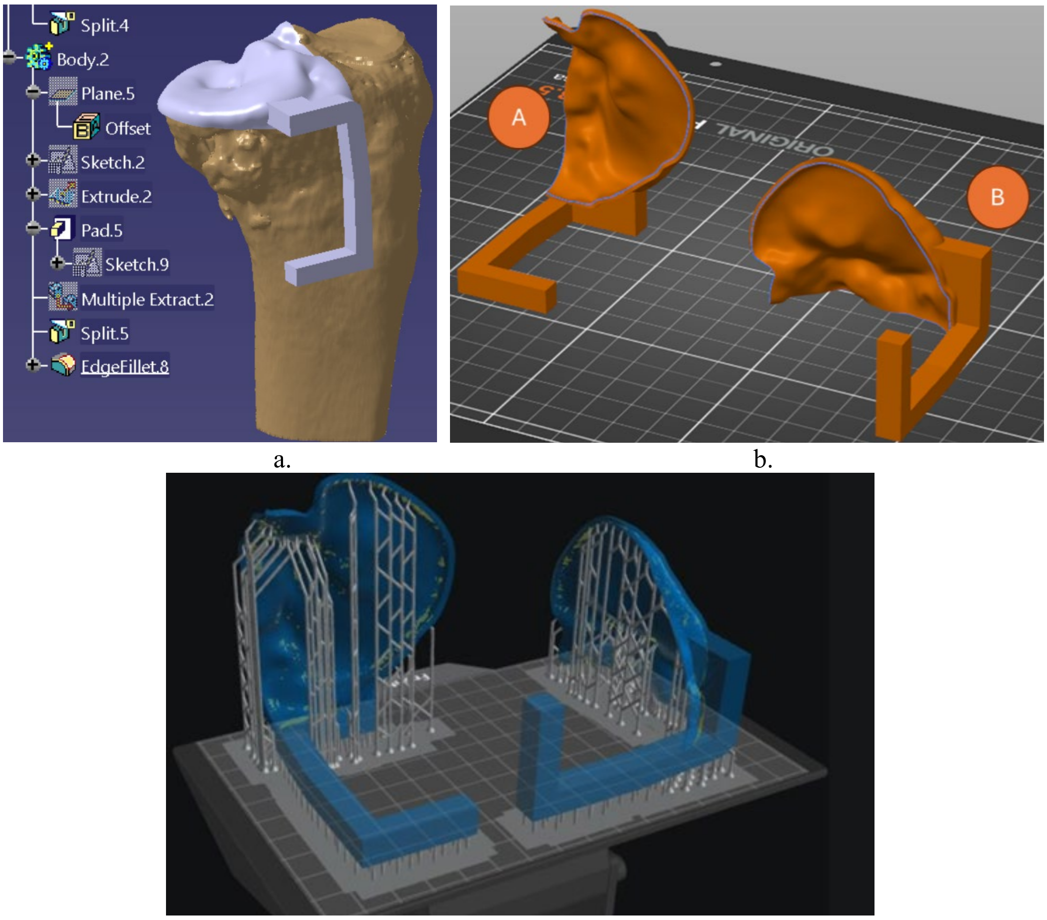
Literature analysis reveals that factors such as process parameters (e.g., layer thickness, printing temperature) [4-5, 9-10], printer type [11], and build orientation [12] were commonly addressed in studies on 3D printing accuracy. Therefore, this research puts the focus on practically relevant, but less-explored variables like as filament moisture, mechanical issues, and specific process settings that are often overlooked, yet likely to influence dimensional accuracy. The aim is to provide additional insights to the existing body of knowledge by analyzing how these overlooked variables can influence the dimensional accuracy and reliability of printed parts.

2. Materials and methods

In this study, AnyCubic Photon Mono 2K MSLA 3D printer and Original Prusa MK3.5 MEX 3D printer were used for manufacturing all samples. A customized surgical guide (Fig. 1) was selected as the benchmark model due to its relevance in applications requiring dimensional accuracy. The guide's design includes both regular and freeform geometrical features that allows multiple build orientations, and offers a balance between practical relevance and printing time and material usage.

The materials used were ABS-like resin [13] (Sunlu, Zhuhai City, CHN) and PLA HP (polylactic acid high performance) filament [14] (ColorFabb, NH). These two materials were selected as being commonly used in the corresponding processes. Also, both categories of materials can be used in applications where printed parts are post-processing in cleaning, disinfection, sterilization-like workflows, which make dimensional stability an important aspect to consider. The study is therefore process-oriented, meaning that the materials are not intended for a direct material-to-material comparison, but to investigate how MSLA versus MEX manufacturing influences dimensional accuracy and repeatability.

The design of the guide was based on the reconstructed model of the patient's tibia, being a variation of the model detailed in [15], with the cutting area placed inside the curved section to enable removal of the tumors shown in Figure 1.



a. b.

c.

Fig. 1. Benchmark part: virtual model based on reconstructed anatomy (a), build orientations A and B in Prusa slicer, 3D prints oriented with support structure in Chitubox slicer (c)

Table 1 lists the analyzed parameters, while Table 2 includes the main process parameters for each process. For MSLA, exposure time was included as a factor although it is often kept fixed through printer/resin profiles, because small variations can influence cure depth and dimensional accuracy.

Table 1

Process parameters and their levels for MEX.

Parameter	**MEX**	**MSLA**
Parameter 1	Filament condition	Exposure time
Levels (Parameter 1)	Dehydrated / Non-dehydrated	Short (2.5 s) / Long (5s)

Parameter 2	Belt tension	Lift Speed
Levels (Parameter 2)	Loose tensioned belt / Belts properly tensioned	Standard (600 mm/min) / High (1800 mm/min)
Parameter 3	Build Orientation	Build Orientation
Levels (Parameter 3)	A / B	A / B

Table 2

Fixed process parameters for MEX and MSLA.

MEX		**MSLA**	
Layer height	0.2 mm	Layer height	0.1 mm
Perimeters	2	Z Lift height	5 mm
Solid layers top/bottom	5/5	Lift distance	5 mm
Infill	100%	Raft shape	Skate
Nozzle temperature	230 °C	Retract speed	1200 mm/min
Bed temperature	60°C	Bottom exposure	40 s

The mechanical calibration of the MEX 3D printer was performed by adjusting the x-axis belt tension and verifying it using the Prusa Belt Tuner web application [16] that measures belt frequency by analyzing the sound captured via a smartphone's microphone. In this research, loose belt corresponded to a measured belt frequency of approximately 51 Hz, and as reference, the recommended optimal belt tension ("just right") was indicated by the application at around 104 Hz.

After manufacturing, each print was scanned using Revopoint MetroX 3D scanner (Fig.2). According to the manufacturer specifications [17], the system has up to 0.03 mm single-frame accuracy and 0.01 mm precision (repeatability), which define the measurement uncertainty floor of the scanning-based metrology used in this study. The resulting meshes were each aligned to the original STL using the ICP algorithm in CloudCompare, and the dimensional deviations were analyzed using cloud-to-mesh (C2M) comparison [18]. All samples were measured, for each process, MEX and MSLA, only the most accurate were included in the analysis, one sample for each configuration.

Four metrics were used for evaluating prints' accuracy: maximum error, standard deviation (std. dev), root mean square (RMS) and Gaussian mean:

- Maximum error represents the largest local deviation between the scanned mesh and nominal model, indicating worst-case dimensional difference;
- Standard deviation (Std. dev) shows how dispersed the local deviations are around the mean error, thus how consistently the scanned mesh aligns with the reference model. Lower standard deviation shows uniform accuracy;

- RMS error is a global measure of overall accuracy as it quantifies the average magnitude of the deviations;
- Gaussian mean reflects the average deviation assuming a normal distribution of errors and offers information on systematic trends such as consistent oversizing or shrinkage.

Fig. 2. 3D scanning of the prints with markers for point clouds alignment

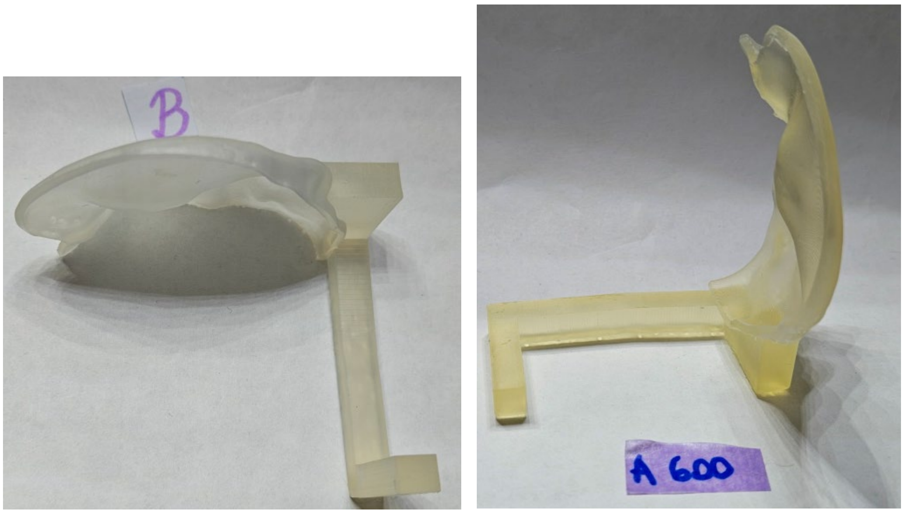
3. Results and discussions

Figure 3 shows two of the MEX prints, one made using non-dehydrated PLA-HP filament in Orientation B (Fig.3a), highlighting the presence of irregularities on the surface in contact with support, and one made of dehydrated filament in Orientation A (Fig.3b) with better quality on all print surfaces. Staircase effect, typical for AM technology, could be observed especially on the freeform surfaces of the print, then of the surfaces printed parallel or perpendicular to the build direction.

Figure 4 presents images of MSLA prints built in two orientations and with different process parameters. One can notice the difference in color given by the difference in exposure time.

a. b.

Fig.3. MEX prints in different configurations of studied parameters: non-dehydrated, B orientation (a); dehydrated, A orientation (b)



a. b.

Fig.4. MSLA prints: Orientation B, 2.5 s exposure time, standard lift speed (a); Orientation A, 5 s exposure time, standard lift speed (b)

In Figures 5-6 are presented screenshots from Cloud Compare software showing the Gauss curves of the deviations between the STL model and the 3D scanned models, as well as the error distribution map, for a MEX print produced with loose belt tension and in Orientation B, and MSLA print made with standard lift speed and 2.5 s exposure time in Orientation A.

In Table 3 are summarized the parameters showing the deviations between the prints and the nominal (STL) model for each studied configuration of MEX prints.

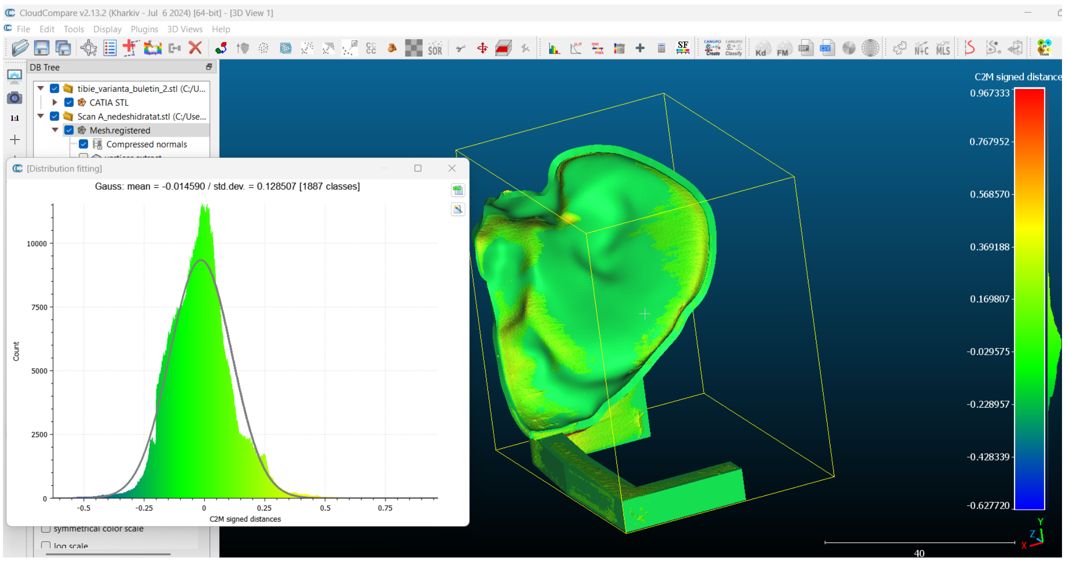


Fig.5. Deviations between the nominal benchmark model and a MEX print, sample 1

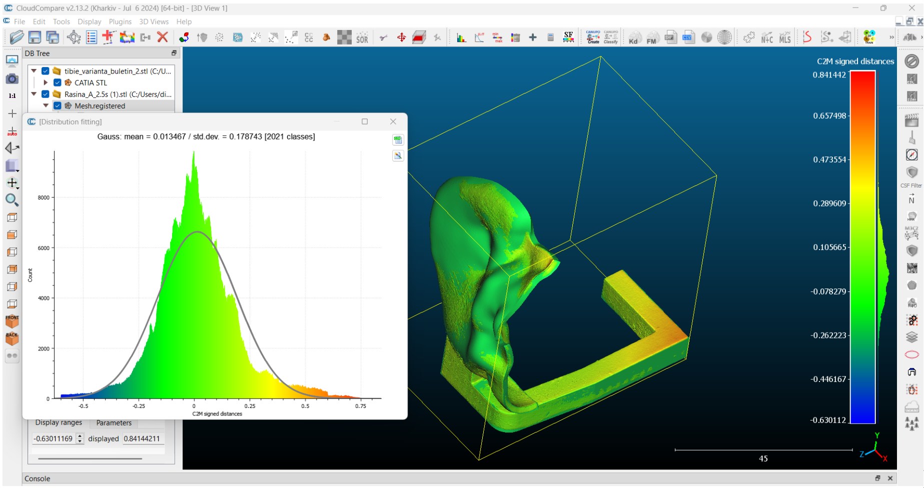


Fig.6.
Deviations between the nominal benchmark model and a MSLA print, sample 9

All deviation-related values in Table 3 are expressed in millimeters. The observed standard deviation values (approximately 0.11–0.14 mm) are significantly larger than the estimated volumetric accuracy of the Revopoint MetroX scanner (which is around 0.04–0.05 mm for the investigated part size). Therefore, the reported deviations primarily reflect manufacturing-induced dimensional variability rather than measurement uncertainty introduced by the scanning process.

Table 3

Deviation-related results for MEX prints and PLA HP filament.

Sample	**Orientation**	**Parameters**	**RMS**	**Max error**	**Gaussian mean**	**Std. dev**
1	A	Non-dehydrated Loose tensed belts	0.129332	0.266049	-0.014590	0.128507
2	B	Non-dehydrated Loose tensed belts	0.136789	0.266308	0.0070382	0.140122
3	A	Dehydrated Loose tensed belts	0.126747	0.267396	-0.0151425	0.121872
4	B	Dehydrated Loose tensed belts	0.115268	0.265973	-0.00455645	0.113906
5	A	Non-dehydrated Properly tensioned belt	0.118268	0.266057	-0.029942	0.114415
6	B	Non-dehydrated Properly tensioned belt	0.128694	0.26626	0.004187	0.128626
7	A	Dehydrated Properly tensioned belt	0.125355	0.266783	-0.018898	0.123923
8	B	Dehydrated Properly tensioned belt	0.117287	0.26579	-0.01511	0.11631

The results on measurements of MEX prints, from Table 3, were analyzed in order to evaluate the effect of filament's moisture on accuracy, as well as the effect of build orientation and belt calibration:

- *Effect of filament dehydration*. Data showed that filament dehydration influenced the dimensional accuracy of PLA-HP prints for both build orientations, with magnitude depending on belt tension values and build orientation, as follows:
    - At loose belt tension, in Orientation A, RMS decreased from 0.129 to 0.127. In Orientation B, RMS decreased more significantly from 0.137 to 0.115;
    - For the loose-tension condition (especially in Orientation B), the Gaussian mean was closer to zero after dehydration, which showed reduced systematic deviation;
    - Maximum error remained almost the same, showing that dehydration mainly influences the overall dimensional consistency (RMS / std. dev), but is not necessarily reducing the most extreme local deviations.
- *Effect of build orientation*:
    - For loose tensed belt, dehydrated filament in Orientation B achieved the lowest RMS error and standard deviation among the loose-tension samples, indicating that this configuration provides the best accuracy when proper material handling is applied.
    - It is also worth noting that Orientation B performed worse than Orientation A when the filament was not dried, but improved substantially after dehydration
    - No filament drying: RMS=0.137 in Orientation B vs. Orientation A=0.129
    - Filament drying: Orientation B improved the most: RMS=0.115, std. dev=0.114
- *Effect of calibration.* Belt calibration positively influenced dimensional accuracy, especially in Orientation A, but the results are more sensitive to variability in Orientation B:
    - In Orientation A, proper belt tension reduced RMS and standard deviation for the non-dehydrated filament, but it also made the Gaussian mean more negative, which indicates a tendency toward undersizing. For the dehydrated filament, the differences between loose and proper tension were small, and the loose condition remained closer to zero in mean deviation.
    - In Orientation B, proper belt tension improved accuracy for the non-dehydrated filament, while for the dehydrated filament, loose

tension produced slightly lower RMS and standard deviation, and the proper tension resulted in a more negative Gaussian mean.

- In general, maximum errors remained almost similar (around 0.266 mm), indicating that belt tension mainly affected global dimensional consistency rather than extreme local deviations.

Table 4 presents the deviations parameters, STL vs. 3D scanned prints, for each of the studied configurations of MSLA samples. All expressed values correspond to milimeters.

Table 4

Deviation-related results for MSLA prints and ABS-like resin.

Sample	Orientation	Parameter	RMS	Max error	Gaussian mean	Std. dev
9	A	2.5 s	0.178743	0.268595	0.013467	0.17925
10	B	2.5 s	0.14983	0.266286	0.02696	0.152236
11	A	5 s	0.219219	0.271168	0.088471	0.200574
12	B	5 s	0.219549	0.271189	0.088724	0.200823
13	A	600 mm/min	0.154216	0.268976	0.06601	0.139375
14	B	600 mm/min	0.138625	0.265951	0.062555	0.123708
15	A	1800 mm/min	0.185074	0.269822	0.102809	0.155071
16	B	1800 mm/min	0.194732	0.267322	0.142025	0.133227

Based on the data for samples 9–12, the influence of build orientation and exposure time on dimensional deviations in MSLA was investigated, and the following information could be extracted:

- *Effect of exposure time*. The results show that longer exposure time increases dimensional deviations in both orientations:
  - In Orientation A, RMS increased with the exposure time from around 0.179 to 0.219, and standard deviation increased from 0.179 to 0.201;
  - In Orientation B, RMS also increased with the exposure time from around 0.150 to 0.220, and standard deviation from 0.152 to 0.201;
  - Gaussian mean also increased significantly at 5 s in both orientations (from about 0.013-0.027 to about 0.088), showing a trend towards systematic oversizing or overcuring;
  - Maximum error increased only slightly (from about 0.266 to about 0.271 mm), indicating that the exposure time has more impact on global consistency than on isolated local deviations;
- *Effect of build orientation*:
  - For the short exposure time, Orientation B performed better, with lower RMS (0.150 vs. 0.179), lower standard deviation (0.152 vs. 0.179);

- For the long exposure time, both orientations exhibited similar deviation values, with almost similar RMS, max error and standard deviation, showing that the excessive exposure prevails over the orientation effects. This suggests that at higher exposure times, resin overcuring is the dominant factor that influences the dimensional deviation;

Samples 13-16 provided information on the *effect of lift speed and orientation over the accuracy*. Two lift speeds were compared, the standard one for the printer and resin, i.e. 600 mm/min (standard), and 1800 mm/min (high). Increasing lift speed was associated with higher RMS and Gaussian mean in both orientations:

- In Orientation A, RMS increased with the lift speed increase from 0.1542 to 0.1851, and standard deviation from 0.1394 to 0.1551;
- In Orientation B, RMS increased from 0.1386 to 0.1947, and standard deviation from 0.1237 to 0.1332;
- Gaussian mean also increased at higher lift speeds in both cases (e.g., from 0.0660 to 0.1028 in Orientation A, and from 0.0626 to 0.1420 in Orientation B) ;
- Maximum error was similar across both lift speeds (0.266–0.270 mm), showing that faster lift speeds do not significantly increase peak local deviations but degrade overall accuracy;
- At high lift speed (1800 mm/min), Orientation B exhibited a higher RMS compared to Orientation A, indicating poorer global accuracy. However, it showed a lower standard deviation (0.1332 vs. 0.1851), suggesting a narrower spread of deviations, combined with a larger systematic bias, as indicated by the highest Gaussian mean (0.1420).

Data in Tables 3-4 allowed determining the best-performing configurations among the analyzed parameter sets for each process and across processes in terms of accuracy. Thus, results showed that for MEX, the best performance (lowest RMS and std. dev) was for sample 4 (Orientation B, Dehydrated, loose tensioned belt). For MSLA, sample 14 (Orientation B, lift speed 600 mm/min) exhibited the lowest RMS and standard deviation. Overall, the most accurate process for the analyzed parameters was MEX.

4. Conclusions

This study investigated the influence of less frequently reported factors on the dimensional accuracy of parts produced by low-cost additive manufacturing systems, specifically MEX (material extrusion) and MSLA (masked stereolithography). Using a benchmark part with a complex design, deviation metrics were evaluated under varying conditions related to material state, mechanical calibration, and printing parameters. The results of this study confirm that multiple factors have distinct and measurable effects on the dimensional accuracy of low-cost systems for the analyzed processes.

RMS and standard deviation quantify dimensional accuracy, but their relevance must be interpreted relative to the nominal part and feature dimensions. In this study, deviations on the order of around 0.1 mm are small relative to global dimensions. However, they can influence the fit and alignment of small features (e.g., holes or thin walls). Therefore, dimensional accuracy in MEX and MSLA parts should be assessed both using the global metrics and feature-level specific requirements.

For MEX process, filament dehydration influenced global dimensional accuracy, with the magnitude depending on belt tension and build orientation. RMS and standard deviation values were notably reduced for the loose belt tension condition across both building orientations, with Orientation B showing the most pronounced improvement. These results suggest that moisture content in the filament is associated with dimensional variability and should be actively controlled. Proper mechanical calibration by belt tension adjustment had a secondary influence. Control over belt tension reduced the standard deviation mainly for the non-dehydrated filament, while for the dehydrated filament the differences between loose and proper tension were smaller and orientation dependent. Under sizing was noted when the Gaussian mean became more negative. Overall, the combination of dehydrated filament, Orientation B, and loose tensioned belts produced the most accurate results within the tested configurations.

In MSLA process, exposure time had the strongest observed influence among the tested factors on the dimensional accuracy of the samples. Shorter exposure durations (2.5 s) produced lower RMS and standard deviation values, while longer exposure times (5 s) led to increased and more uniform global deviations. These trends suggest that overcuring resin causes geometric distortion regardless of build orientation. Lift speed showed a similarly consistent influence with higher lift speeds determining greater dimensional deviation across both orientations. The most accurate results were obtained at a lift speed of 600 mm/min, with Orientation B providing better consistency. The data indicates that minimizing overexposure and mechanical stress during separation phases is essential for preserving dimensional accuracy for the resin-based process.

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