Indian Journal of Engineering & Materials Sciences
Vol. 33, June 2026, pp. 259-268
DOI: 10.56042/ijems.v33i03.27413

Estimation of measurement uncertainty of 3-D metal printed specimen of H13 tool steel fabricated via metal fused filament fabrication process using 3D scanner

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Received: 09 January 2026 ; accepted: 08 May 2026

This work has presented dimensional characterization and a "Guide to the Expression of Uncertainty in Measurement" (GUM) compliant measurement uncertainty evaluation of metal parts fabricated by metal fused filament fabrication process (M-FFF). A high-resolution handheld optical 3D scanner has been used for dimensional measurement of the printed specimens. Four different geometries have been printed from H13 tool steel, washed, sintered, and then digitally inspected to investigate dimensional deviations and further quantify the reliability of scanner-based metrology. Each specimen has been scanned three times, and dimensional deviation analyses have been conducted by means of CAD-to-scan comparisons using Artec Studio 19. Systematic deviations based on printing-induced shrinkage, surface topology, and scanning conditions have been revealed, and measured deviations across all samples have ranged from –0.999 mm to +0.989 mm. Measurement uncertainty has been estimated via both Type A (repeatability) and Type B (instrument and environmental factors) contributions. The following factors have been considered for Type B uncertainty evaluation: scanner point accuracy, resolution, alignment error, thermal expansion, and distance-dependent error. Repeatability and alignment/registration error have been identified as the main uncertainty contribution factors. The combined standard uncertainty has resulted in 122.7 µm, with an expanded uncertainty of approximately ±0.247 mm at k=2.015, 95% confidence level. It has been concluded that the presented and validated uncertainty budget offers a realistic tolerance band for industrial qualification of MFFF components, while enhancing the reliability of non-contact optical metrology. The findings have allowed a robust framework to be established for metrology-driven process validation, quality assurance, and industrial adoption of MFFF, which caters for very diverse applications, ranging from aerospace, automotive, and tooling to medical devices, part repairing, complex part dimension measurement and defense manufacturing.

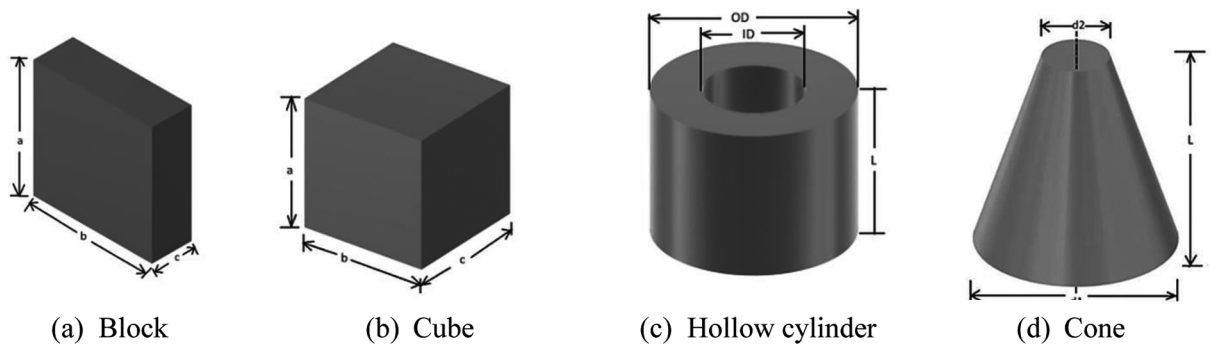
Keywords: 3D scanner, Additive manufacturing, Measurement uncertainty budget, Reverse engineering, Tolerance

1 Introduction

The rapid development of additive manufacturing technologies, sometimes referred to as 3D printing, are increasingly competitive with traditional manufacturing methods. This growth imposes the necessity of determining the dimensional and geometrical accuracy of the manufactured parts[1-3]. The evaluation of dimensional accuracy is important to technologists and decision-makers, since metrological results directly influence decisions concerning 3D printer calibration, maintenance, and the execution of custom engineering orders. However, the dimensional and shape accuracy of AM-built components depends strongly on process parameters such as layer thickness, scan path, extrusion quality, and thermal behaviour during fabrication. Variations in these parameters can lead to deviations in part quality and geometry[4,5]. Dimensional deviations and shrinkage are intrinsic challenges in metal additive manufacturing processes and recent work also explores compensation methods using 3D scanning and inverse deformation approaches[6]. Parts produced via additive processes often deviate from their nominal CAD dimensions due to inherent factors such as printer resolution, build orientation, thermal gradients, and even the measurement method used[7,8].

In geometrical analysis of AM parts, reverse engineering workflows are typically aided by advanced tools of metrology. Dial calipers, Coordinate Measuring Machines (CMM), and several types of 3D scanners such as laser scanners and structured-light scanners are commonly employed for the metrological analysis of these components. Among all these methods, portable and high-precision optical scanners have been found to be highly advantageous for the measurement of free-form surfaces, scanning of biologically inspired shapes, and creating dense

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(a) Block (b) Cube (c) Hollow cylinder (d) Cone

Fig. 1 — Geometric configurations designed for scanning (a) Block, (b) Cube, (c) Hollow cylinder, and (d) Cone.

Table 1 — Dimensions of 3-D printed samples.

Sample name	Dimensions (in mm)		
Block	a = 15	b = 15	c = 5
Cube	a = 15	b = 15	c = 15
Hollow cylinder	OD = 20	ID = 10	L = 15
Cone	d_1=5	d_2=15	L=15

point clouds at a rapid pace[9,10]. However, the accuracy of such scanners can be affected by the environmental factors. Materials with highly reflective, metallic, or glossy surfaces often introduce substantial challenges for optical systems, since direct and specular reflections saturate camera sensors, disrupt fringe projection, and degrade reconstruction quality[11]**.** Several studies have shown that structured-light scanners exhibit higher noise, incomplete data, and increased height-profile deviation when scanning metal substrates due to specular reflection and brightness variation[12,13]. To address this limitation, the application of matte developer sprays or anti-reflective coatings is widely recommended, as they effectively suppress reflections and enable the scanner to capture more uniform and accurate surface data[14,15].

Present work integrates high-resolution optical 3D scanning with a complete GUM-compliant measurement uncertainty budget to quantify measurement reliability for metal AM parts. Most studies report only dimensional error with no contribution of scanner point accuracy, alignment error, repeatability, thermal drift, or uncertainty, which are very critical issues for the industrial qualification of scanner-based metrology. This work has performed a comprehensive dimensional deviation analysis on four distinct geometries made of H13 steel using MFFF, identified geometry-specific error trends, and presents the detailed measurement uncertainty budget for handheld optical scanning of MFFF components. Also identifies the key sources of errors for process validation, quality assurance, and industrial adoption of MFFF to produce functional metal parts.

2 Materials and Methods

2.1 Specimen fabrication

The FDM (fused filament fabrication) method, also known as FFF (fused filament fabrication), is one of the most popular 3D printing methods. These technologies are classified under material extrusion (MEX) according to the ISO/ASTM 52900:2021 standard[16]. In the present work this additive manufacturing process has been utilized for printing the specimens by using H13 tool steel filament. H13 tool steel filament consists of metal powder, wax and additives. The complete printing process involves washing and sintering to remove the wax and additives, followed by densification through atomic diffusion process during sintering. For the present investigation, four different geometrical configurations (Fig. 1) were modeled and produced by metal fused filament fabrication process (MFFF). Three nominally identical specimens were fabricated for each configuration to the dimensions stated in Table 1.

The general methodological workflow adopted in this study is presented in Fig. 2. All the fabricated specimens were digitized using Hand-held, blue rays based, industrial grade 3D scanner, which is able to capture intricate surface details and complex geometries with an accuracy of up to 0.05 mm and resolution of 0.1 mm. Every specimen was mounted on a rotary table during scanning, allowing for complete 360° acquisition of its surface. Acquired point-cloud data were subsequently aligned, registered, and compared against original CAD models generated in

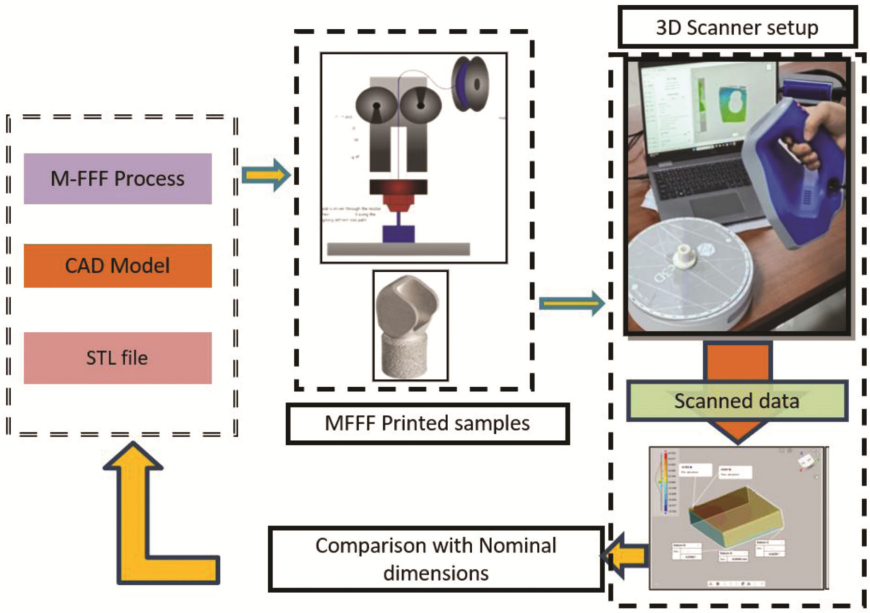


Fig. 2 — Complete methodology adopted for metrology analysis.

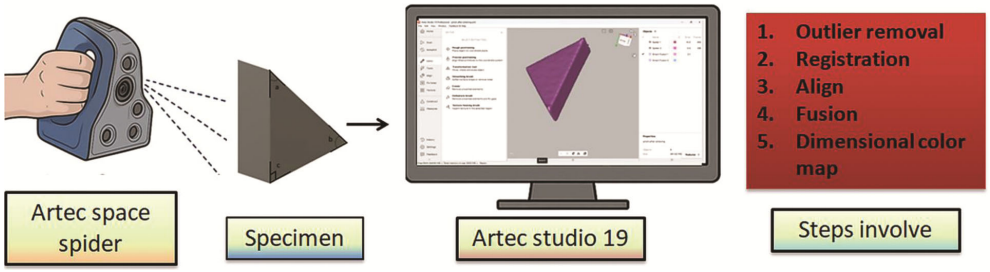


Fig. 3 — Illustration of complete scanning process.

Table 2 — Specification of 3D scanner.

Scanner type	handheld
3D point accuracy	0.05 mm
3D resolution	0.1 mm
3D accuracy over distance	0.05mm + 0.3mm/m
Working distance	0.2 - 0.3 m
Thermal expansion error	± 0.01905 mm
Alignment error	0.10 mm

Autodesk Fusion 360. Dimensional deviation analysis were performed using multiple datum planes to ensure precise alignment and robust error quantification. Linear and angular measurements were extracted using Artec Studio 19 professional metrology software. The technical specifications of the 3D scanner are summarized in Table 2.

2.2 Measurement by 3D scanner

The complete process of scanning is presented in Fig. 3. Dimensional measurement using the Artec Space Spider 3D scanner and Artec Studio 19 Professional involves scanning the object to capture high-resolution geometry, cleaning and aligning the scan data, and generating a precise fused mesh. Each specimen scanned three times and the dimensions deviations were measured for all three samples and the average values and standard deviations of the three measurement are reported in Table 3. Onscreen images of measurements in Artec Studio 19 professional software are depicted in Fig. 4.

2.3 Dimensional characterization

Dimensional characterization refers to the systematic measurement and evaluation of the geometric features of a manufactured part or material and overall dimensional deviation from the intended CAD model. It enables precise CAD-to-scan deviation analysis of geometric inaccuracies, distortions, shrinkage, warping, or surface irregularities due to layer-by-layer fabrication or post-processing. Industries are using 3D scanning for first article

Table 3 — 3D scanner observations.

Sample name/ No.	Dimension	Nominal size (mm)	Average (mm)	SD (mm)	% Deviation
Cube 1	a	15	15.300	0.040	-2.000
	b	15	15.253	0.150	-1.687
	c	15	15.207	0.095	-1.380
Cube 2	a	15	15.168	0.072	-1.120
	b	15	15.265	0.044	-1.767
	c	15	15.357	0.128	-2.380
Cube 3	a	15	15.415	0.052	-2.767
	b	15	15.221	0.079	-1.473
	c	15	15.312	0.133	-2.080
Block 1	a	15	15.140	0.164	-0.933
	b	15	15.213	0.101	-1.420
	c	5	4.900	0.100	2.000
Block 2	a	15	15.396	0.035	-2.640
	b	15	15.246	0.106	-1.640
	c	5	5.162	0.071	-3.240
Block 3	a	15	15.086	0.075	-0.573
	b	15	15.189	0.096	-1.260
	c	5	5.259	0.109	-5.180
Hollow cylinder 1	OD	20	20.270	0.061	-1.350
	ID	10	10.307	0.061	-3.070
	L	15	15.140	0.053	-0.933
Hollow cylinder 2	OD	20	20.188	0.058	-0.940
	ID	10	10.255	0.105	-2.550
	L	15	15.171	0.060	-1.140
Hollow cylinder 3	OD	20	20.165	0.058	-0.825
	ID	10	10.216	0.114	-2.160
	L	15	15.181	0.112	-1.207
Cone 1	d1	5	4.893	0.090	2.140
	d2	15	15.067	0.153	-0.447
	L	15	15.333	0.115	-2.220
Cone 2	d1	5	5.066	0.069	-1.320
	d2	15	15.186	0.077	-1.240
	L	15	15.170	0.069	-1.133
Cone 3	d1	5	4.958	0.044	0.840
	d2	15	15.166	0.076	-1.107
	L	15	15.143	0.048	-0.953

inspection to validate parts against engineering drawings and adherence to aerospace, automotive, defense, and medical standards. Its capability to capture freeform, lattice, and topology-optimized geometries makes it an essential solution for verifying complex AM designs that are impossible to measure with traditional tools.

In reverse engineering applications, 3D scanners produce high-resolution digital models of legacy components, used parts, or tooling and die that need refurbishment, thus enabling fast reproduction and design modification, even without available CAD data. It also supports the quantitative optimization of build-parameter-dependent dimensional deviations, sintering shrinkage in metal additive manufacturing like MFFF and binder jetting, and the impact of laser power, scan speed, or infill pattern. 3D scanning continues to help improve non-destructive testing through insights into surface defects such as porosity breakout, staircase effects, and incomplete fusion[17]. Such devices are also employed in the tooling industry for qualifying insert moulds, conformal cooling channels, and die features produced through additive manufacturing, which have undergone

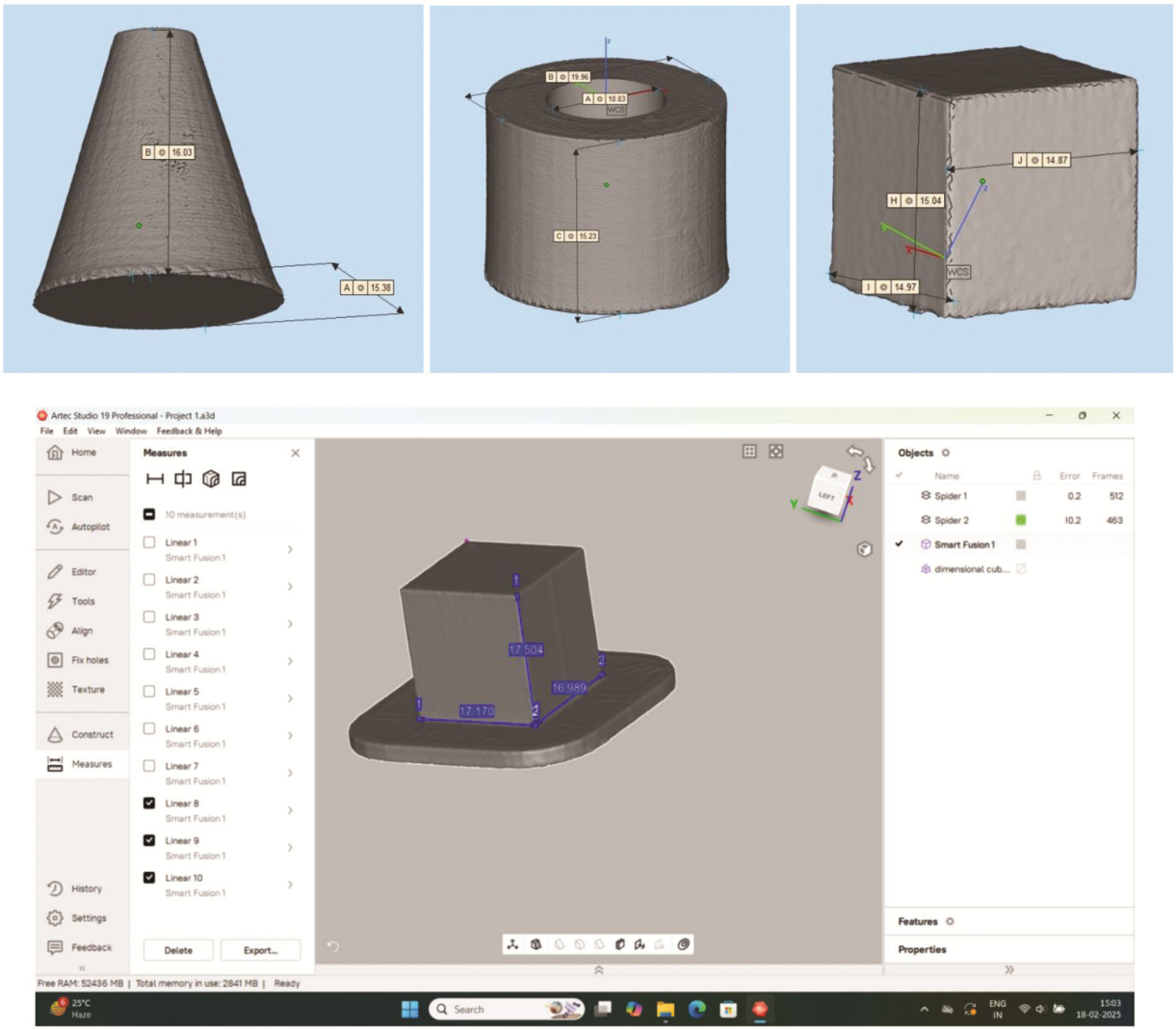


Fig. 4 — Dimension measurement of scanned specimen by Artech studio 19 Professional software.

post-processing heat treatment[18]. Overall, 3D scanning is an valuable metrology and validation tool, thereby enhancing accuracy, reliability, and industrial penetration of additive manufacturing. Dimensional analysis using a 3D scanner in additive manufacturing (AM) is extremely useful because it provides high-accuracy, non-contact measurement of printed parts, helping engineers evaluate how closely the printed component matches the original CAD model. This also helps in reverse engineering to manufacture or repair the part[19].

Measurement uncertainty evaluation in 3D scanning involves quantifying the doubt associated with the measured dimensions obtained from non-contact optical systems, ensuring confidence in the measurement results and distinguishing true process-induced deviations from errors arising due to scanner hardware, operator handling, surface characteristics, or environmental conditions. It supports in defining reliable tolerance limits and ensures compliance with ISO/ASTM standards for validation. In this work, the geometrical features of the printed samples were characterized using a high-precision 3D scanner, and the measurement uncertainty was evaluated following the "Guide to the Expression of Uncertainty in Measurement (GUM)" through both Type A (statistical repeatability) and Type B (instrument- and environment-related) approaches[20,21].

Type A uncertainty was calculated from repeated scans of the samples by using Equation 1, determining the mean, standard deviation, and corresponding standard uncertainty while Type B uncertainty is

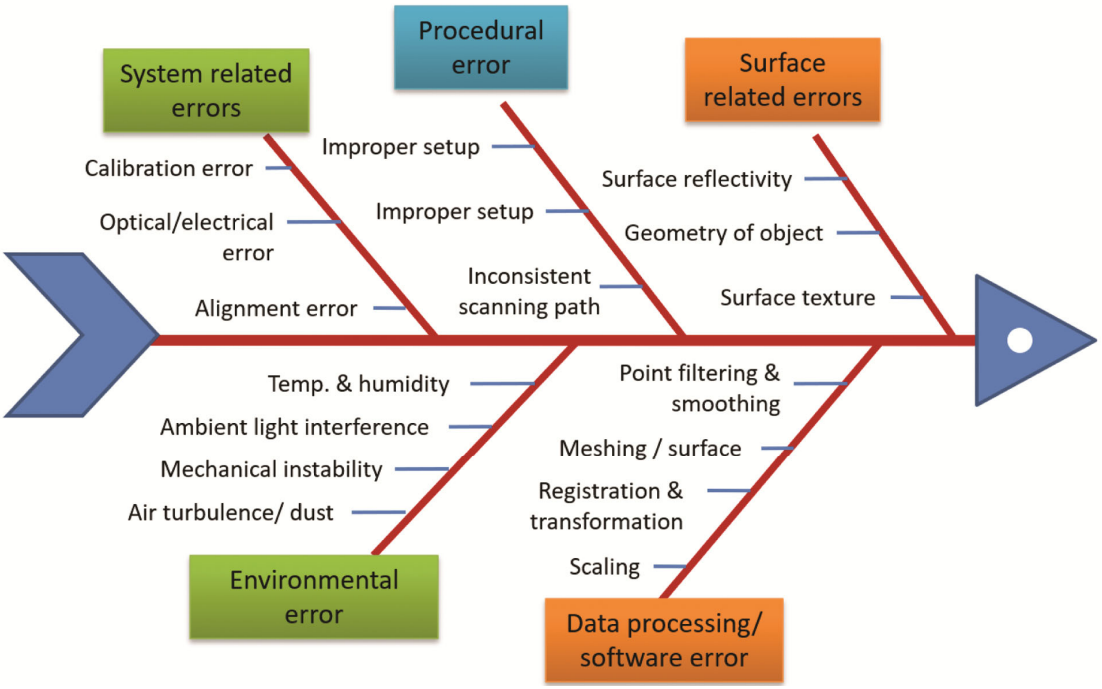


Fig. 5 — Cause and effect diagram for various sources of error in 3D scanning process.

given by Equation 2, which includes contributions from scanner resolution, 3D point accuracy, calibration accuracy, surface reflectivity, environmental stability, alignment error, and software reconstruction parameters[22].

$$u_A = \frac{SD}{\sqrt{n}} \quad \ldots (1)$$

$$u_c{}^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2{}_{x_i} \quad \ldots (2)$$

$$U_E = k u_C(y) \quad \ldots (3)$$

Expanded uncertainties (expressed in Equation (3)) were then evaluated using Equation (3) and a fishbone diagram (Fig. 5) summarized potential uncertainty sources affecting linear, circular, and angular features extracted from the scanned point cloud[23]. In Equation (3) k is the coverage factor and effective degree of freedom expressed by using this relation

$$\vartheta_{eff} = \frac{u^4_{c(y)}}{\sum_{i=1}^{n} \frac{u^4_{(xi)}}{v_i}} \quad \ldots (4)$$

3 Results and Discussion

3.1 Measurement uncertainty budget evaluation

The average values and standard deviations (SD) of the linear dimensions extracted from the 3D-scanned point clouds of the printed samples are summarized in Table 3. Each specimen was scanned three times and the dimensions was measured for each scan, and the Type A uncertainty was computed from the repeated measurements using Equation (1). The dimension showing the highest SD was selected for detailed uncertainty evaluation. A comprehensive measurement uncertainty budget, incorporating all scanner-related contributors, is presented in Table 5, while the expanded uncertainties for all measured features are reported in Table 4. Among all the scanned features, the block 1, dimension a exhibited the highest SD and corresponding Type A uncertainty, and was therefore chosen as the representative case for developing the complete measurement uncertainty budget.

3.2 Deviation analysis

Figure 6 presents the CAD-to-scan deviation analysis of four 3D-printed geometries—Block, Cube, Cone, and Hollow Cylinder—captured using the Artec Space Spider 3D scanner and processed in Artec Studio 19. In each case, the scanned mesh (shown in green) is aligned with its nominal CAD model using defined datums, enabling accurate dimensional verification based on Geometric Dimensioning and Tolerance Principles (GD&T) principles. It is an international symbolic language used to define the size, form, orientation, and location of features on an engineering drawing[24]. A color deviation scale illustrates surface variations, where

Table 4 — Measurement uncertainty evaluation of samples.

Sample name/ No.	Dimension	Nominal size (mm)	Average (mm)	SD (mm)	Type A uncertainty, U_A	Combined uncertainty, Uc	Expanded uncertainty (microns)
Cube 1	a	15	15.300	0.040	0.023	0.082	138.330
	b	15	15.253	0.150	0.087	0.117	226.777
	c	15	15.207	0.095	0.055	0.095	167.125
Cube 2	a	15	15.168	0.072	0.041	0.088	182.964
	b	15	15.265	0.044	0.025	0.082	167.826
	c	15	15.357	0.128	0.074	0.107	247.759
Cube 3	a	15	15.415	0.052	0.030	0.084	171.066
	b	15	15.221	0.079	0.046	0.090	188.688
	c	15	15.312	0.133	0.077	0.110	253.094
Block 1	a	15	15.140	0.164	0.095	0.123	247.153
	b	15	15.213	0.101	0.058	0.097	229.210
	c	5	4.900	0.100	0.058	0.097	171.143
Block 2	a	15	15.396	0.035	0.020	0.081	164.986
	b	15	15.246	0.106	0.061	0.099	216.392
	c	5	5.162	0.071	0.041	0.088	181.311
Block 3	a	15	15.086	0.075	0.043	0.089	185.863
	b	15	15.189	0.096	0.056	0.096	205.857
	c	5	5.259	0.109	0.063	0.100	219.530
Hollow cylinder 1	OD	20	20.270	0.061	0.035	0.086	146.324
	ID	10	10.307	0.061	0.035	0.085	145.524
	L	15	15.140	0.053	0.031	0.084	142.433
Hollow cylinder 2	OD	20	20.188	0.058	0.033	0.085	174.157
	ID	10	10.255	0.105	0.061	0.099	214.914
	L	15	15.171	0.060	0.034	0.085	174.962
Hollow cylinder 3	OD	20	20.165	0.058	0.034	0.085	174.591
	ID	10	10.216	0.114	0.066	0.102	227.550
	L	15	15.181	0.112	0.065	0.102	223.544
Cone 1	d1	5	4.893	0.090	0.052	0.093	163.009
	d2	15	15.067	0.153	0.088	0.118	228.986
	L	15	15.333	0.115	0.067	0.103	186.167
Cone 2	d1	5	5.066	0.069	0.040	0.087	179.643
	d2	15	15.186	0.077	0.045	0.090	187.824
	L	15	15.170	0.069	0.040	0.088	181.092
Cone 3	d1	5	4.958	0.044	0.025	0.082	166.504
	d2	15	15.166	0.076	0.044	0.090	186.452
	L	15	15.143	0.048	0.028	0.083	169.310

Table 5 — Measurement uncertainty budget for 3D scanner.

Sources of Error	DOF	Limits	Unit	Probability distribution	Factor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution µm	Length independent	Square of uncertainty (microns)
3D point accuracy	∞	0.05	mm	R	1.732	0.029	1	28.868	28.867	833.333
Resolution (quantization)	∞	0.1	mm	R	1.732	0.029	1	28.868	28.868	833.333
distance dependent	10	0.05+0.3 mm/m	mm	R	1.732	0.05+0.3*L	0.3L			
						0.0545		31.465		990.083

(*Contd.*)

Table 5 — Measurement uncertainty budget for 3D scanner. (*Contd.*)

Sources of Error	DOF	Limits	Unit	Probability distribution	Factor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution µm	Length independent	Square of uncertainty (microns)
thermal expansion error	10	0.01905	mm	R	1.732	0.011	1	10.999	10.999	120.974
Alignment/registration error	10	0.1	mm	R	1.732	0.058	1	57.737	57.737	3333.529
Repeatability	2	94.516	µm	N		94.516	1	94.516	94.516	8933.333
Combined Uncertainty									microns	122.656
Expanded,		*k*=2.015							microns	247.153

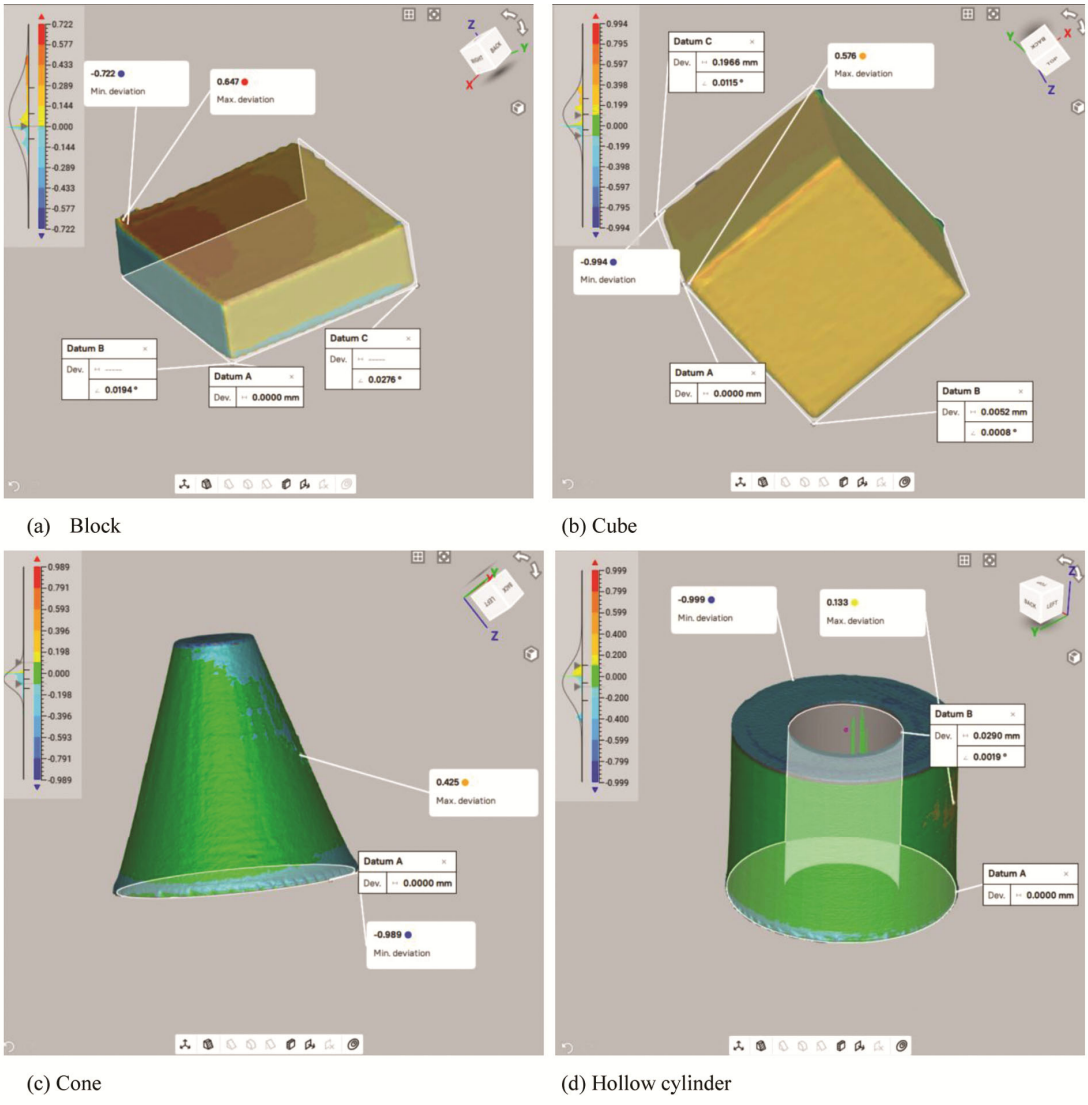


Fig. 6 — Dimensional analysis in Arctech 3D scanner (a) Block, (b) Cube, (c) Cone and (d) Hollow cylinder.

green indicates close conformity to the CAD geometry, while blue and yellow/red signify negative and positive deviations, respectively. For the block and cube, planar datums A, B, and C stabilize alignment, with small deviations observed across the faces, reflecting print-induced distortions. The cone

Table 6 — Result of scanned specimens as minimum deviation and maximum deviation.

Sample name	Minimum deviation (mm)	Maximum deviation (mm)
Cube 1	-0.196	0.567
Cube 2	-0.233	0.354
Cube 3	-0.768	0.286
Block 1	-0.722	0.647
Block 2	-0.687	0.175
Block 3	-0.421	0.132
Hollow cylinder 1	-0.999	0.133
Hollow cylinder 2	-0.752	0.231
Hollow cylinder 3	-0.254	0.472
Cone 1	-0.425	0.989
Cone 2	-0.123	0.175
Cone 3	-0.314	0.354

shows deviation concentrated near the top region due to its inclined surface and scanning angle effects, while the cylindrical sample demonstrates inner and outer surface deviation evaluation using datums placed on the base plane and inner cylindrical surface.

Measured deviations results presented in Table 6 across all samples show that minimum deviations range from –0.123 mm to –0.999 mm, while maximum deviations lie between 0.132 mm and 0.989 mm. Simple geometries such as cubes and blocks exhibit relatively smaller deviation bands (approximately –0.23 to 0.65 mm), whereas complex curved parts like hollow cylinders and cones show larger deviation ranges (up to –0.999 mm and +0.989 mm), indicating higher sensitivity to printing and scanning challenges. This quantitative evaluation reinforces the visual deviation maps by demonstrating that geometrical complexity directly influences dimensional variation.

Across all four geometries, the deviation maps highlight the dimensional fidelity of the printed parts and reveal localized form errors, providing a comprehensive assessment of printing accuracy and surface variation using high-resolution optical scanning. Dimensional deviations occur due to combined effects of 3D printing inaccuracies—such as thermal shrinkage, warping, surface roughness, and the staircase effect—and 3D scanning limitations, including resolution, surface reflectivity, and reconstruction errors. Misalignment during CAD-to-scan registration and imperfections in datum features can also introduce localized deviations. These factors cause some regions to appear oversized (positive deviation) or undersized (negative deviation) when compared to the ideal CAD geometry. Such deviations are normal and help evaluate the true dimensional accuracy of the printed parts.

3.3 Uncertainty analysis

This measurement uncertainty budget quantifies how different error sources of the Artec Space Spider contribute to the overall measurement uncertainty for the scanned specimen (results expressed in microns). Each row lists a source, its degrees of freedom (DOF), the worst-case limit used, the assumed probability distribution, the resulting standard uncertainty. The main contributors are repeatability (largest single contributor ≈ 59% of total variance) and alignment/registration error (≈ 22%), while point accuracy, resolution, distance-dependent error and thermal expansion make smaller contributions (~5–7% each, thermal ≈0.8%). The combined standard uncertainty $U_c = 122.7$ µm, and using the coverage factor k=2.015 gives an expanded uncertainty U ≈ 247.15 µm (≈ ±0.247 mm) i.e., it can state the scanned dimension with about 95% confidence as measured ±0.247 mm. This measurement uncertainty helps in deciding tolerance band for producing parts in industrial applications.

4 Conclusion

The present study provides a full GUM-compliant dimensional uncertainty evaluation of Metal Fused Filament Fabrication (MFFF) components, using a high-resolution handheld optical 3D scanner, to tackle the critical metrological gaps usually present in AM inspection. By investigating four different geometries of H13 steel, the work identified geometry dependent deviation trends and quantified the individual contributions of scanner point accuracy, alignment error, resolution, thermal drift, and repeatability-in addition to pinpointing repeatability and alignment as dominant uncertainty sources. Measured deviations across all samples range from –0.999 mm to +0.989 mm, with cubes and blocks showing smaller variation bands compared to curved geometries. Hollow cylinders and cones exhibit the largest deviations, reflecting their higher sensitivity to printing and scanning limitations. Overall, the results confirm that increasing geometric complexity leads to greater dimensional variation. An expanded uncertainty of approximately ±0.247 mm, at k = 2.015 (95% confidence level), considering the different sources present in 3D scanning, offers a realistic tolerance band

for the reliable qualification of MFFF parts. The validated uncertainty budget enhances confidence in industrial applications such as first-article inspection, process validation, reverse engineering dimensional certification of functional metal components, and quality assurance in aerospace, automotive, tooling, medical, and military sectors. Overall, this work provided a solid and immediately usable framework for developing a metrology framework for optical scans of metal AM components. Optical scanning methods now represent an industry-preferred method for accurate, repeatable, and standardized dimensional verification of metal AM parts.

In the future, research in this area will expand the scope for dimensional characterization beyond academic study to other complex geometrical configurations associated with common Additive Manufacturing (AM) components used in industry (i.e., Lattice Structures, thin-walled regions, Internal Channels). In addition, there will also need to be further exploration of the feasibility and reliability of the measurement techniques by performing comparative studies with several different types of Metrology Systems, including Coordinate Measuring Machines (CMM), Laser Scanners and Computed Tomography (CT) Scanning Systems. Once a relationship has been established between the Printing Parameters and Sintering Conditions along with Dimensional Deviation and Measurement Uncertainty, Predictive Modelling and Compensation Modelling efforts can be developed to improve the dimensional accuracy of AM components. By integrating the Dimensional Deviation and Measurement Uncertainty data into Digital Twin frameworks and aligning the Metrology Procedures to the latest ISO/ASTM Standards, improved quality assurance methodologies can be established which can expand the industrial application of Metal Additive Manufacturing Metrology.

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