The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLIX-B1-2026
XXV ISPRS Congress 2026 "From Imagery to Understanding", Commission I, 4–11 July 2026, Toronto, Canada

Geometrical Accuracy Investigations of Handheld 3D Scanners in Comparison: Low-Cost vs. High-End

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KEYWORDS: 3D, accuracy, comparison, geometry, meshes, reference bodies.

ABSTRACT:

Handheld 3D scanners have gained increasing importance in recent years due to their flexibility and declining acquisition costs. While high-end systems provide standardized accuracy specifications, affordable devices often lack reliable and comparable benchmarks. This paper evaluates the geometric accuracy of three low-cost handheld 3D scanners (Revopoint Pop 3 Plus, Revopoint MetroX, 3DMakerPro Moose 3D scanner) compared to two high-end systems (Hexagon MARVELSCAN, Hexagon Absolute Arm with AS1 scanner), using the ZEISS Atos 5 structured light system as reference. Five different test objects with varying material and geometric properties were used for practical assessment. Results reveal significant differences regarding flatness, detail fidelity, and robustness: while some low-cost scanners achieve remarkable accuracies, their performance is less stable under varying conditions. The accuracy of both Revopoint scanners is low, and they exhibit systematic deviations. In some cases, however, the Moose scanner achieves accuracy levels close to those of high-end scanners. High-end systems, in contrast, consistently provide high precision and reproducibility. This study provides a well-founded classification of current handheld 3D scanners and practical guidance for their application in science, industry, and education.

1. INTRODUCTION

The digitisation of physical objects using 3D scanning technology has become essential in many fields, including industrial quality control, medical applications, and the documentation of cultural heritage. As demand for precise 3D data has grown, the handheld 3D scanner market has diversified significantly in recent years. Alongside expensive industrial instruments costing tens of thousands of euros, there is now a growing range of affordable systems costing a few hundred euros, which are aimed at semi-professional and private users.

A key issue is that the accuracy specifications of low-cost scanners are often inaccurate or inadequately documented. This makes it difficult to evaluate their performance objectively or to make direct comparisons with well-established, high-end systems. Against this background, the key question is whether low-cost scanners can be considered a viable technical and economic alternative.

This work aims to systematically investigate the geometric accuracy of a selection of handheld 3D scanners. Three low-cost systems purchased for educational purposes are compared with two high-end devices and evaluated based on five reference objects in practical conditions. The analysis considers factors such as robustness of data acquisition, efficiency and cost-effectiveness, as well as geometric accuracy.

The results allow for a more detailed classification of current scanner performance, providing users with a solid basis on which to select the most appropriate system. At the same time, they shed light on the limitations and potential of affordable scanners, offering valuable insights for future developments and research.

2. RELATED WORKS

In recent years, the performance of handheld 3D scanners has been investigated in various application contexts. While there are already standardised accuracy benchmarks for stationary systems such as laser scanners or photogrammetry, the available data on mobile handheld 3D scanners, particularly in the low-cost segment, remains heterogeneous.

Several studies have examined the use of handheld scanners in medical applications. For instance, Rudolf et al. (2017) examined the use of handheld scanners in capturing body shapes for garment design, thereby confirming their suitability for ergonomically challenging processes. Andrews et al. (2019) used handheld 3D scanning as a minimally invasive technique to take anthropometric measurements of newborn babies. Xia et al. (2019) compared various body measurement techniques, including the use of a 3D stationary scanner, a 3D handheld scanner and tape measurement. Furthermore, Skrzypiec et al. (2024) analysed the reproducibility of prosthetics applications, emphasising the importance of standardised testing procedures. Seo et al. (2025), for instance, validated the Revopoint MINI for use in medical studies on mice, showing that inexpensive scanners can deliver the accuracy and reproducibility required for volumetric analyses.

A handheld scanner was used by Wu et al. (2024) to create exact 3D models of fruits for finite element simulations in agricultural engineering.

Kersten et al. (2016a, 2016b, 2018) conducted the first comprehensive comparison of seven handheld 3D scanners from different price ranges. The study revealed a wide range of achievable accuracies and offered users initial guidance. Most low-cost systems exhibited systematic deviations due to unstable scale calibration. However, these findings are only partially

https://doi.org/10.5194/isprs-archives-XLIX-B1-2026-263-2026

Manufacturer	System	Precision [mm]	Range [m]	Weight [g]	Technology	Price (ca.) [€]
Hexagon	Abs. Arm + scanner	±0.006–0,04	1.5–4.5	10000	laser lines / tactile	100,000–150,000
Hexagon	MARVELSCAN	±0.02–0,03	0.2–0.5	1300	blue structured light	40,000–60,000
Revopoint	POP 3 Plus	±0.08	0.15–0.4	190	IR structured light	700
Revopoint	MetroX	±0.03	0.2–0.4	385	blue structured light	1,200
3DMarkerPro	Moose	±0.03	0.02–1.5	280	blue structured light	700

Table 1. Technical specification (by manufacturers) of the handheld scanning devices used for the geometric accuracy investigations.

applicable to current low-cost models due to rapid advances in hardware and software.

Lachat et al. (2017) examined the geometric accuracy of the Faro Freestyle 3D handheld scanner using laboratory experiments and a study of real-life archaeological artefacts. Meanwhile, Allegra et al. (2017) tested handheld 3D scanning systems for use in cultural heritage applications. Furthermore, Ameen et al. (2018) compared two scanners using different technologies to digitise complex automotive parts, assessing their accuracy and efficiency.

In summary, existing research suggests that handheld scanners have a wide range of applications and can, in some cases, achieve high levels of accuracy. However, a systematic, metrologically sound analysis that directly compares low-cost and high-end devices in terms of robustness, efficiency and cost-effectiveness is lacking. This study addresses this research gap through practical geometric investigations.

3. INVESTIGATED HANDHELD 3D SCANNING SYSTEMS AND REFERENCE OBJECTS

3.1 Handheld 3D scanning systems

Five handheld 3D scanners, representing a variety of price categories and technologies, were selected for this study (Figure 1). These low-cost scanners were chosen for their low combined price of €2,500 and to investigate their performance. The ZEISS ATOS 5 structured light system, developed by Carl Zeiss GOM Metrology, was used as the reference due to its certified accuracy in accordance with VDI/VDE 2634 (2012). It was chosen for its availability and high precision of 10–30 µm. It is designed for high-speed 3D scanning and rapid data processing at a higher resolution (ZEISS Industrial Quality Solutions, 2023). The ATOS 5 uses an LED as a light source, has a measuring area of 170 × 140 – 1000 × 800 mm, and has a working distance of 880 mm. It can also measure up to 12 million points per scan.

Figure 1. Handheld 3D scanners for the geometric investigations (f.l.t.r) - Hexagon Absolute Arm with AS1 scanner, Hexagon MARVELSCAN, 3DMakerPro Moose, Revopoint MetroX, and Revopoint Pop3 Plus (Display scale of systems is not uniform)

The low-cost category included the Revopoint Pop3Plus (Revopoint, 2025a), the Revopoint MetroX (Revopoint, 2025b) and the 3DMakerPro Moose (3DMakerpro, 2025). These systems were priced between €700 and €1,200 and are based on structured light technologies. The high-end systems examined were the Hexagon MARVELSCAN (Hexagon Manufacturing Intelligence, 2025a) and the Hexagon Absolute Arm with AS1 scanner (Hexagon Manufacturing Intelligence, 2025b), which are priced in the five- to six-digit range and have certified accuracies between 0.02 and 0.05 mm. The technical specifications of the handheld scanning systems are summarised in Table 1.

3.2 Reference objects

The following five reference objects with varying geometries and material properties were used for the benchmarking test (Figure 2): a planar granite slab (size 300×300 mm²) for flatness error analysis, a gypsum bust of Einstein (height of 160 mm) for organic forms and fine details, a so-called "Testy" (height of 380 mm) from the Institute for Computer Science at Humboldt University in Berlin (Reulke & Misgaiski, 2012) for complex geometries, a 3D printed staircase model (size 100×100×100 mm) for dimensional accuracy and edge sharpness, which consists of five evenly spaced steps, each 20 mm high and deep, and a Moai figure from Easter Island (height 140 mm and a maximum horizontal dimension of approximately 60×55 mm) with porous material to challenge reflection properties. The 3D staircase model was printed using a Prusa printer with polylactic acid material. The 0.4 mm line thickness of the print nozzle enables reproducible production with clearly defined geometric edges.

Figure 2. Overview of the reference objects used (f.l.t.r): granite plate, Einstein bust, Testy model, staircase model and Moai figure.

For the purposes of comparison, all five figures were scanned using a high-precision structured-light system (ATOS 5), which was developed by Carl Zeiss GOM Metrology. The two reference bodies (Testy and Einstein's bust) and the granite slab have previously been used to analyse the geometric accuracy of the first generation of handheld 3D scanners (Kersten et al., 2016b; Kersten et al., 2016c; Kersten et al., 2018), while Testy and the Einstein bust have also been used to analyse the geometric accuracy of low-cost systems (Kersten et al., 2016a) and mobile phones (Kersten et al., 2024).

4. DATA ACQUISITION AND PROCESSING

Data acquisition was conducted under practical conditions in the Geodetic Lab at HafenCity University Hamburg between January and March 2025. All scanners were calibrated according to the manufacturers' specifications. While the Revopoint Pop 3 Plus and MetroX required user calibration with reference plates, the 3DMakerPro Moose relied on factory-set calibration parameters. The high-end systems applied standardised calibration procedures according to VDI/VDE standards. The ZEISS ATOS 5, with its advanced camera technology, strong blue light source and powerful software, served as the reference system and formed the basis for all 3D comparisons. Scanning of the reference objects with the ATOS 5 was carried out in January 2024 and 2025 (only staircase model) by GDV Systems + Solutions GmbH in Bad Schwartau, in the Geodetic Laboratory of HafenCity University Hamburg (HCU). The aim was to achieve the complete, high-resolution digitisation of the test objects to evaluate the respective systems' properties in terms of resolution, detail recognition, and geometric accuracy.

Scanning of the objects was carried out in February and March 2025 using the Revopoint POP 3 Plus and MetroX (Figure 3). Prior to data acquisition, user-guided calibration was performed using the supplied calibration plate in the Revo Scan 5 software. However, as no verifiable calibration data was output, complete traceability in accordance with metrological standards was not possible. To maximise detail accuracy, turntable mode was used, with minimum rotation angles configured between individual scans to ensure high coverage and sufficient overlap of the scan data. Target markers were positioned in the immediate vicinity of the test objects to support visual tracking. For larger objects such as the Testy, additional markers were placed on the object itself. During the scanning process, there were repeated disconnections between the turntable and the control software, significantly delaying the measurement process. It also became apparent that the available computing resources were not being used efficiently. Although GPU acceleration was enabled in the software, computationally intensive tasks were still being processed exclusively by the CPU, negatively impacting system responsiveness and processing speed.

Figure 3. Scanning of the stairways on the turntable with MetroX (left) and scanning of the Testy on a black plastic mat with targets.

The test objects were scanned using the 3DMakerpro Moose in March 2025. The system was calibrated by inserting the supplied calibration file into the software; therefore, no user-guided or traceable calibration procedure was performed. Hand-held EasyScan mode was used for scanning, as TableScan mode was impractical. This was particularly evident with larger objects, where the limited number of permissible scans and the increased susceptibility to errors during registration restricted the capture process. Markerless object tracking was performed using either texture-based or geometry-based methods. Due to the largely unstructured nature of the test objects, the geometry-based variant was used. The scans were performed in high-resolution 'Fine Mode'. Several individual scans were required to capture all surfaces of the objects completely.

Data acquisition using the MARVELSCAN and the Absolute Arm was carried out on 24 February 2025 under the supervision of a Hexagon technical operator (Figure 5). Prior to commencing the MARVELSCAN measurement, a user-guided calibration was conducted using the supplied calibration plate (Figure 4). In contrast, the Absolute Arm with the AS1 scanner was factory calibrated and, according to the specifications, did not require on-site recalibration. The MARVELSCAN's integrated photogrammetry module was not used in this investigation. The scanner's self-localisation was based on a marker-supported reference field installed on the measurement base. This meant that placing additional markers directly on the test object was unnecessary. The measurement was performed manually and was characterised by short scanning times and immediate visual feedback via the user interface to support efficient data acquisition. For complex geometries, the scan mode was adjusted during recording to acquire the most complete, high-quality data possible.

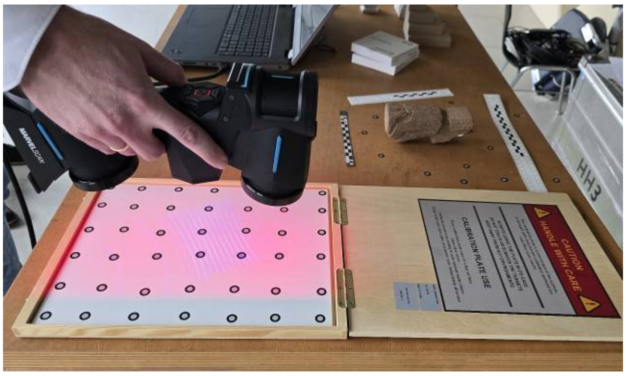

Figure 4. Calibration of the MarvelScan using a precise calibration plate.

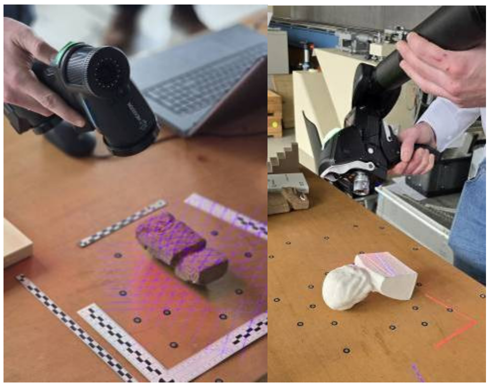

Figure 5. Scanning of the Moai figure with MARVELSCAN (left) and scanning of the Einstein bus using the Absolute Arm with AS1-Scanner (right).

As part of the data acquisition process, tactile single-point measurements were taken using the probe module, while 3D scans of entire surfaces were performed using the Hexagon Absolute Arm 7-Axis with AS1 Scanner (Figure 5, on the right). These two measurement methods could be switched between directly on the system without the need for realignment or recalibration. The spatial localisation of the measuring head was carried out via the integrated absolute encoders in all joints of the arm. This enabled measurements to be taken without the need for external reference marks. Progress during the measurement process was supported by an OLED display on the device, as well as visual and acoustic feedback signals. The guided design of the measuring arm did not adversely affect usability and enabled reliable data acquisition without significant interruptions.

Subsequent data processing was carried out using software for the Revo Scan 5 (Revopoint POP 3 Plus) and the Revo Scan 5 MetroX (MetroX scanner). First, individual point clouds were generated from the partial scans at a defined resolution of 0.1 mm for the POP 3 Plus and 0.05 mm for the MetroX. The Moose scan data were processed in JMStudio-Scan software (specified workflow by manufacturer), the MARVELSCAN scans in PolyWorks, and the Absolute Arm 7-Axis with AS1-Scanner data in SpatialAnalyzer. Before merging, the point clouds were cleaned using integrated isolation and overlay algorithms to eliminate unconnected or redundant data areas. The cleaned partial scans were then merged into a consistent overall point cloud, which was subsequently subjected to further structural optimisation. Based on this point cloud, a triangulated surface model was created. The cleaned partial scans were merged to create a consistent overall point cloud, which was then structurally optimised. A triangulated surface model was generated based on this point cloud and further refined using isolation methods and software-supported filling of local data gaps. The final geometry was exported in STL format for subsequent geometric analysis. This analysis was based on mesh-to-mesh comparisons between the scanned data and the reference models, and was performed using Geomagic Wrap software. The analysis included best-fit alignment, colour-coded deviation maps and statistical evaluations.

5. RESULTS FOR THE REFERENCE OBJECTS

5.1 Granite surface plate

The granite surface plate revealed significant differences between the scanner categories when computed using GOM Inspect software. High-end systems achieved deviations (average distance) of less than 0.05 mm with excellent reproducibility. In contrast, low-cost scanners exhibited greater variation and significant systematic effects, as demonstrated by the colour-coded visualisation in Figure 6. The MetroX produced acceptable deviations of 0.29 mm, whereas the Pop 3 Plus produced the worst result, with an average distance of 1.7 mm. The Moose, on the other hand, was slightly more accurate than the Pop 3 Plus in terms of the average distance, but less stable during extended scans.

As can be seen in Table 2, there are considerable differences in the characteristic deviations between the individual systems. The average deviation ranges from 0.04 mm to 1.68 mm, and there is also significant variation in the standard deviation. Higher-priced systems, such as the Absolute Arm and the MARVELSCAN from Hexagon, are characterised by low average deviations and consistent colour coding of surface deviations (Figure 6). In contrast, lower-cost devices such as the Pop 3 Plus, MetroX and Moose exhibit pronounced surface distortions and increased scatter. Furthermore, significant differences in maximum distances were observed between low-cost and high-end scanning systems, as confirmed by measured differences of five selected points to the adjusted plane (Table 2). Notably, the two Revopoint scanners have a high number of triangles and a large file size compared to the other three scanners. The same is true for the following test objects. However, scanning was deliberately carried out at the highest resolution to obtain the best possible results for these two systems.

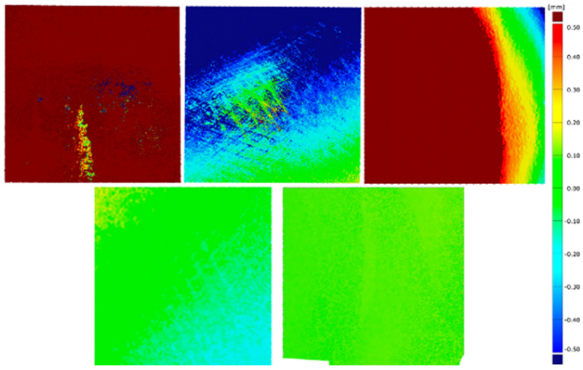

Figure 6. Surface deviations [mm] of the 3D meshes of the granite plate (GOM Inspect: test data vs. adjusted plane) f. l. t. r.: top – Revopoint Pop 3 Plus, Revopoint MetroX, 3DMakerPro Moose; bottom – Hexagon MARVELSCAN and Hexagon Absolute Arm [Span of coloured coded scale bar ±0.5 mm].

Systems [mm]	P3	MX	Mo	MS	AS1
# Triangle [Tsd]	39850	7396	847	700	332
File Size [MB]	1951	1228	142	113	55
Average dist.	1.68	-0.40	0.89	-0.04	0.05
Std. deviation	0.96	0.29	0.60	0.08	0.03
Max dist +	3.85	1.41	1.89	0.25	0.13
Max dist -	-3.85	-1.41	-1.89	-0.25	-0.13
Dev @P1	1.54	-0.26	1.69	-0.07	0.07
Dev @P2	2.08	-1.16	1.70	0.06	0.06
Dev @P3	2.51	-0.63	-0.24	-0.04	0.10
Dev @P4	2.62	0.05	0.11	-0.21	0.06
Dev @P5	2.72	-0.06	0.99	-0.06	0.04
P3…Pop 3 Plus, MX…MetroX, Mo…Moose, MS…MARVELSCAN, AS1… Absolute Arm & AS1					

Table 2. Measurement error in flatness of the granite plate, as determined by distances and deviations to the adjusted plane using the data of handheld 3D scanning systems.

5.2 Einstein bust

The bust of Albert Einstein is used to analyse the geometric accuracy of the 3D scanning systems under investigation. The model is particularly well-suited to evaluating the quality of data acquisition and reconstruction due to its combination of low texture and geometric complexity, which emphasises detail fidelity.

All of the handheld scanning systems tested were capable of capturing the entire test object. The measured surface deviations for all models were within a tolerance range of ±0.5 mm, except for the Revopoint scanners, which had a maximum deviation of ±7.6 mm. Despite this high level of capture capability, there were clear differences in the quality of the reconstructed geometries. These differences are discernible both visually (Figure 7) and statistically (Table 3). A visual comparison reveals clear quality differences between the scanning systems used (Figure 7). In particular, the low-cost scanners show a comparatively inconsistent pattern of deviation. In addition to distortions occurring over large areas, systematic differences from the reference geometry are evident, particularly in the geometrically complex areas around the ears. By contrast, the higher-priced systems from Hexagon produce a homogeneous and visually consistent reconstruction of the object geometry. The resulting surfaces are characterised by low deviation amplitudes and high surface coherence, indicating reliable capture performance. It is also noteworthy, however, that the 3DMakerPro Moose achieves the most statistically precise parameters of the low-cost scanners, which are very close to those of the high-end scanners. This system has a very low mean value and minimal standard deviation, suggesting high accuracy. Nevertheless, visual analysis reveals locally limited systematic effects in the front part of the bust (the orange-red area) that indicate weaknesses in the reconstruction.

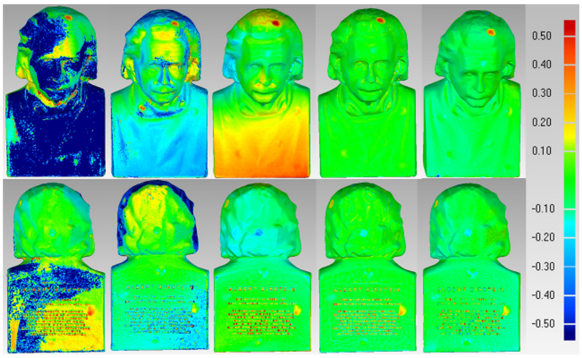

Figure 7. Surface deviations [mm] of the 3D meshes of the Einstein bust (Geomagic Wrap: test data vs. reference object). Top: front, bottom: back, f. l. t. r. – Revopoint Pop 3 Plus, Revopoint MetroX, 3DMakerPro Moose, Hexagon MARVELSCAN and Hexagon Absolute Arm.

System [mm]	P3	MX	Mo	MS	AS1
# Triangle [tsd]	26382	55689	869	1688	545
File size [MB]	1288	2719	42	82	26
Average dist.	-0.58	-0.15	0.03	-0.00	-0.05
Av distance +	0.30	0.19	0.13	0.04	0.04
Av distance -	-0.93	-0.21	-0.06	-0.03	-0.06
Std. deviation	1.26	0.47	0.13	0.13	0.06
Max distance +	7.60	7.60	0.77	0.71	2.80
Max distance -	-7.60	-7.60	-0.42	-0.35	-1.88
Span	15.20	15.20	1.19	1.06	4.68
P3…Pop 3 Plus, MX…MetroX, Mo…Moose, MS…MARVELSCAN, AS1… Absolute Arm & AS1					

Table 3. Distances between the 3D model of the Einstein bust using handheld systems compared to the ATOS 5 reference model.

5.3 Testy

In geometric analysis, the Testy model is used to evaluate the scanning accuracy and depth resolution of 3D scanning systems. Due to its complex geometry and largely texture-free surface, the model is particularly effective at identifying deviation behaviour related to the system. Thus, the complex Testy model revealed the limitations of low-cost devices. In contrast, high-end systems captured the geometry fully and consistently.

Comparisons of surfaces scanned using different 3D systems reveal clear differences in the quality of surface representation and geometric accuracy. Even a visual analysis of the colour-coded representations of deviation reveals significant differences in the extent and distribution of surface deviations (Figure 8). Artifacts can be seen in the data of the Pop 3 Plus and MetroX systems, particularly at transitions between subsurfaces. This may indicate weaknesses in surface reconstruction or insufficient stability in the registration of the point clouds. Additionally, when comparing the Pop 3 Plus and MetroX systems, individual reference markers remain visible on the surface of the object, and to a much lesser extent with the 3DMakerPro Moose system. This suggests that the smoothing or filtering processes during post-processing are limited.

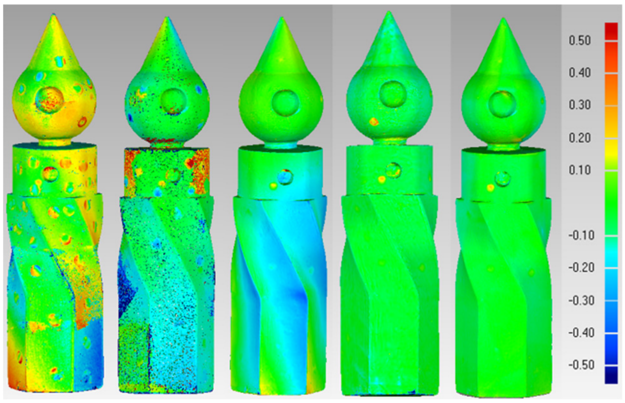

Figure 8. Surface deviations [mm] of the 3D meshes of the Testy (Geomagic Wrap: test data vs. reference object). F. l. t. r. – Revopoint Pop 3 Plus, Revopoint MetroX, 3DMakerPro Moose, Hexagon MARVELSCAN and Hexagon Absolute Arm.

System [mm]	P3	MX	Mo	MS	AS1
# Triangle [tsd]	23949	43492	1322	1326	517
File size [MB]	1169	2124	65	61	25
Average dist.	-0.05	-0.08	-0.03	-0.04	-0.03
Av distance +	0.24	0.73	0.12	0.05	0.02
Av distance -	-0.44	-0.29	-0.11	-0.05	-0.04
Std. deviation	1.06	1.57	0.19	0.12	0.05
Max distance +	15.3	15.3	12.8	0.68	9.26
Max distance -	-15.3	-15.3	-0.8	-15.3	-0.51
Span	30.6	30.6	13.6	15.9	9.77
P3…Pop 3 Plus, MX…MetroX, Mo…Moose, MS…MARVELSCAN, AS1… Absolute Arm & AS1					

Table 4. Deviations of handheld 3D scanning systems of the Testy compared to the ATOS 5 reference model.

The visual analysis is supported by the quantitative comparison values presented in Table 4. In particular, the mean values and standard deviations of the measured surface deviations confirm the earlier qualitative observations. The Pop 3 Plus and MetroX systems from Revopoint both exhibit significantly higher mean deviations and dispersion, as illustrated in the colour-coded visualisation (Figure 8). Conversely, the 3DMakerPro Moose results are approaching the values of higher-class systems again, although some systematic effects are visible in the lower part of the Testy (blue area). The MARVELSCAN and AS1 scanners demonstrate high consistency with the reference model, delivering stable and precise measurement results. However, due to the high complexity of the object, there are also slightly higher maximum deviations with the two high-end scanners (Table 4).

5.4 Staircase model

The staircase model was used to analyse the resolution, scale accuracy and shape fidelity of the 3D scanning systems. The combination of regular geometry pronounced edge transitions, and a largely texture-free surface makes the accurate scanning of the available geometric information challenging. The staircase model confirmed the superior dimensional accuracy and edge sharpness of high-end systems, which reproduced steps with deviations of less than 0.05 mm. In contrast, low-cost scanners tended to blur edges. The Moose scanner achieved the best results in its category (Table 5), whereas the Pop 3 Plus exhibited distinct rounding and shows also significant systematic effects. The consistently negative deviation of the Revopoint Pop 3 Plus and MetroX scans of the staircase model indicates systematic under-dimensioning of the geometry (Figure 9). This behaviour suggests a scale error in the reconstruction process whereby the recorded distances are consistently smaller than the actual dimensions of the component.

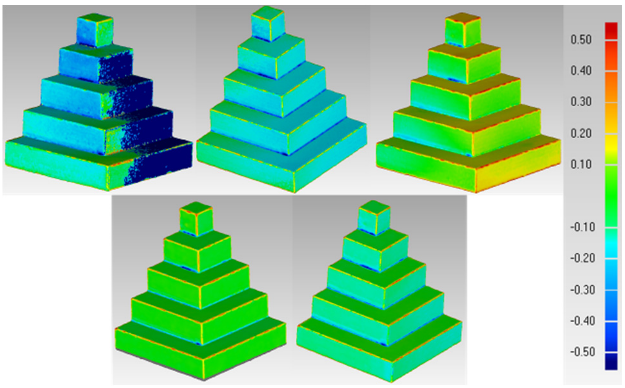

Figure 9. Surface deviations [mm] of the 3D meshes of the staircase model (Geomagic Wrap: test data vs. reference object). Top f. l. t. r. – Revopoint Pop 3 Plus, Revopoint MetroX, and 3DMakerPro Moose, bottom Hexagon MARVELSCAN (left) and Hexagon Absolute Arm (right).

A visual comparison of the staircase model shows that the MARVELSCAN provides the most consistent representation of the stair geometry overall. The surfaces appear evenly captured, the edges are clearly contoured and there are no significant local deviations, indicating consistent and stable surface reconstruction (Figure 9).

The Hexagon Absolute Arm with the AS1 shows a recognisable pattern of surface deviation distribution, primarily on vertical structural surfaces. In contrast, no comparable patterns of deviation are visible on horizontal surfaces. Apart from this directional tendency, the reconstruction shows a homogeneous surface structure with consistent geometric reproduction.

However, all scanners struggle to reproduce the sharp edges of the stairs correctly in the reconstructed model in comparison to the reference model of ATOS 5.

System [mm]	P3	MX	Mo	MS	AS1
#Triangle [tsd]	17038	39515	857	492	141
File size [MB]	831	1929	42	24	9
Average dist.	-0.41	-0.13	0.09	0.02	-0.05
Av distance +	0.15	0.13	0.12	0.05	0.07
Av distance -	-0.47	-0.15	-0.06	-0.02	-0.09
Std. deviation	0.66	0.10	0.10	0.08	0.10
Max distance +	6.99	0.96	0.81	0.86	3.50
Max distance -	-7.09	-7.08	-0.55	-0.65	-0.75
Span	14.08	8.04	1.36	1.51	4.25
P3…Pop 3 Plus, MX…MetroX, Mo…Moose, MS…MARVELSCAN, AS1… Absolute Arm & AS1					

Table 5. Deviations of handheld 3D scanning systems of the stairway model compared to the ATOS 5 reference model.

5.5 Moai figure

The Moai figure is used to examine the quality of geometric scanning under challenges related to materials and reflections. Due to its porous surface, fine microstructure, and high-contrast, differently reflecting surfaces, the object places high demands on the stability and recording accuracy of optical data capture. It should also be noted that the test object was marked with targets during the reference recording with ATOS 5, which were absent during subsequent measurements with the comparison systems. There are therefore local deviations in the relevant areas (red dots in Figure 10) that are not attributable to the recording properties of the respective scanners and are therefore not considered in the evaluation.

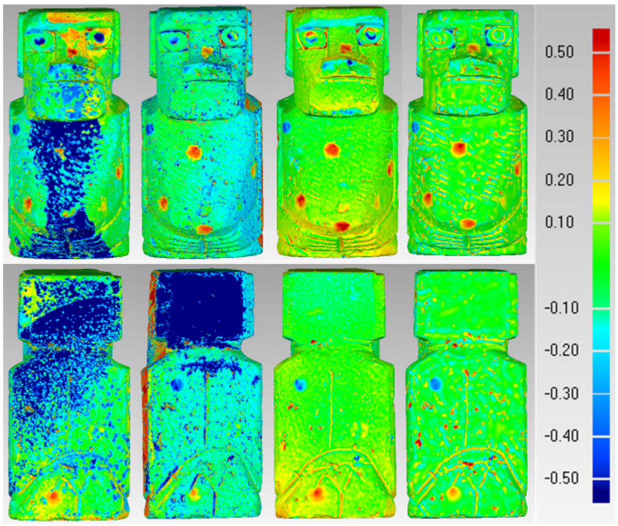

Figure 10. Surface deviations [mm] of the 3D meshes of the Moai figure (using Geomagic Wrap: test data vs. reference object). Top: front, bottom: back. F. l. t. r. – Revopoint Pop 3 Plus, Revopoint MetroX, 3DMakerPro Moose, and Hexagon MARVELSCAN.

As no data has been collected using the Hexagon Absolute Arm for this model, this system cannot be included in the evaluation below. The MARVELSCAN performed well in this respect, whereas low-cost scanners struggled. While the Moose scanner occasionally produced acceptable models after post-processing, the Pop 3 Plus and MetroX suffered from noise, tracking losses, systematic effects and incomplete surfaces.

Comparing the 3D surface data with the ATOS 5 reference dataset reveals clear differences in the scanning systems' capture quality. In particular, the Revopoint devices (Pop 3 Plus and MetroX) show larger, more irregular deviations, as can be seen in both the colour distribution of the deviation representations (Figure 10) and the statistical parameters (Table 6). By contrast, the 3DMakerPro Moose and Hexagon MARVELSCAN demonstrate a more consistent and uniform deviation distribution, suggesting a more stable surface reconstruction process.
The eye region of the Moai is a particularly challenging area for modelling, as the combination of sharply defined black-and-white structures and complex local geometries places high demands on optical sensor technology and data processing. Scans captured by the Pop 3 Plus and MetroX show significant deviations in the pupil region. While the Moose scanner captures the central structures more consistently, it struggles with the transition to the pupil. In contrast, the MARVELSCAN consistently captures this area stably and accurately.

System [mm]	P3	MX	Mo	MS
#Triangle [tsd]	5655	19756	355	305
File size [MB]	275	965	17	15
Average dist.	-0.24	-0.24	0.05	0.01
Av distance +	0.28	0.62	0.08	0.07
Av distance -	-0.57	-0.41	-0.05	-0.05
Std. deviation	1.19	1.07	0.10	0.10
Max distance +	7.00	7.00	1.50	4.86
Max distance -	-7.00	-7.00	-1.81	-5.95
Span	14.00	14.00	3.31	10.81
P3…Pop 3 Plus, MX…MetroX, Mo…Moose, MS…MARVELSCAN, AS1… Absolute Arm & AS1				

Table 6. Deviations of handheld 3D scanning systems of the Moai figure compared to the ATOS 5 reference model.

6. DISCUSSION AND EVALUATION

The results of the geometric accuracy investigations demonstrate that the precision, robustness and detail fidelity of handheld scanners differ substantially depending on price and technology. High-end systems consistently deliver highly accurate results, making them suitable for industrial applications requiring sub-millimetre precision. However, their high acquisition costs and operating complexity restrict their use to professional contexts.

Of the low-cost devices tested, the Moose scanner performed well, achieving accuracies similar to those of high-end scanners in some tests, although there was greater variation. It may therefore be suitable for applications requiring moderate levels of accuracy, such as in education or during the early stages of development. By contrast, the Pop 3 Plus and MetroX exhibited significant stability and detail reproduction issues, limiting their application to simple geometries. Furthermore, the two Revopoint scanners produce point clouds and triangular meshes that are up to 280 times larger than those produced by the two high-end scanners and the Moose scanner when high resolution is taken into account. The large amount of data and file size cause performance issues when processing the data. However, scanning was deliberately carried out at the highest resolution to achieve the best possible results. Nevertheless, it makes sense to reduce the amount of data appropriately in order to make it manageable.

From an economic perspective, affordable scanners provide wider access to 3D scanning technologies, especially for new user groups. However, reduced robustness and the increased need for post-processing may offset their apparent cost advantage. Overall, low-cost scanners complement, but do not replace, high-end devices.

Despite methodological limitations, the present results provide important insights into the performance and applicability of handheld 3D scanners in practical situations. They thus lay the groundwork for further research and a thorough examination of the evaluation and selection of such systems in an application-oriented context.

7. CONCLUSION AND OUTLOOK

This paper presents the results of investigations into the geometric accuracy of 3D handheld scanners. Five handheld 3D scanners were tested for geometric accuracy, and the results were evaluated in terms of the complete system, taking into account data acquisition, data processing, geometric results and price. The analysis comprised three cost-effective systems — the Revopoint Pop 3 Plus, the Revopoint MetroX and the 3DMakerPro Moose — and two professional, high-priced systems: the Hexagon MARVELSCAN and the Hexagon Absolute Arm 7-Axis in combination with the Absolute Scanner 1. Reference objects, which were generated using the ZEISS Atos 5, were used to evaluate the recorded data. The results of these investigations show that the performance of handheld 3D scanners can vary greatly, and that the choice of system depends heavily on the application and the operator's experience. High-end scanners produced highly accurate and detailed results consistently, whereas low-cost devices produced mixed results. Hexagon's higher-priced systems are characterised by high dimensional accuracy and precision. Notably, they are robust with regard to different material properties, enabling the creation of resilient models regardless of the nature of the object being scanned. Comprehensive accuracy tests revealed a heterogeneous result in terms of the accuracy potential of low-cost handheld scanners. In a direct comparison, the Moose scanner from 3DMakerPro proved to be the most accurate system and the most robust against different material properties. Conversely, the accuracy study of the Pop 3 Plus and MetroX from Revopoint indicates very unstable scan fusion, manifesting as high noise behaviour and extensive deviations.

Based on the results of this study, there are clear discrepancies between the high- and low-cost handheld 3D scanners examined. Overall, the high-priced systems can be classified as more geometrically precise, robust, and time efficient. However, when considering cost-effectiveness, the high purchase price means that the aspects decisive for the respective application must be weighed up differently.

Overall, it can be said that the low-cost scanners examined achieved high levels of accuracy in some areas, approaching the level of high-priced systems under certain conditions. However, the analysis revealed limitations in terms of the systems' efficiency, robustness and traceability. For this reason, these systems are primarily recommended for semi-professional use where the focus is on design, conceptual or documentary requirements. Potential applications include digital capture for design processes, visualisation of prototypes, 3D printing of non-critical components, and archaeological documentation with moderate tolerance requirements.

Future research should include a larger sample of devices, establish standardised testing procedures and examine long-term stability. Ultimately, improvements in the performance of affordable scanners may reduce the gap with high-end systems for certain applications.

ACKNOWLEDGEMENTS

The authors would like to thank Ingo Jahn and Claudia Rajczak of GDV Systems + Solutions GmbH in Bad Schwartau for scanning the reference objects using a Zeiss ATOS 5 structured light projection system. We would also like to express our sincere thanks to Hexagon Manufacturing Intelligence Germany GmbH, and in particular to Mr Mats Witte, for providing the scanning systems and expert technical support when recording the test objects.

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