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Article

Investigations of the Geometrical Accuracy of Handheld 3D Scanning Systems

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Summary: An increasing number of handheld scanning systems by different manufacturers is becoming available on the market. However, their geometrical performance is little-known to many users. Therefore, the Laboratory for Photogrammetry & Laser Scanning of the HafenCity University Hamburg has carried out geometrical accuracy tests with the following systems in co-operation with the Bochum University of Applied Sciences (Laboratory for Photogrammetry): DOTProduct DPI-7/DPI-8, Artec Spider, Mantis Vision F5 SR, and Creaform HandySCAN 700. In the framework of these comparative investigations geometrically stable reference bodies were used. The appropriate reference data was acquired by measurements with two structured light projection systems (AICON smartSCAN and GOM ATOS I 2M). The comprehensive test results of the different test scenarios are presented and critically discussed in this contribution.

Zusammenfassung: *Untersuchungen zur geometrischen Genauigkeit von handgeführten 3D-Scanningsystemen*. Handgeführte Scannersysteme verschiedener Hersteller sind in zunehmendem Maße am Markt verfügbar, jedoch ist über ihre geometrische Leistungsfähigkeit bei vielen Anwendern wenig bekannt. Daher hat das Labor für Photogrammetrie & Laserscanning der HafenCity Universität Hamburg in Zusammenarbeit mit der Hochschule Bochum (Labor für Photogrammetrie) geometrische Genauigkeitsuntersuchungen mit folgenden Systemen durchgeführt: DOTProduct DPI-7/DPI-8, Artec Spider, Mantis Vision F5 SR und Creaform HandySCAN 700. Im Rahmen dieser vergleichenden Untersuchungen wurden geometrisch stabile Referenzkörper eingesetzt. Die zugehörigen Referenzdaten wurden durch Messung mit zwei Streifenprojektionssystemen (AICON smartSCAN und GOM ATOS I 2M) erfasst. Die umfassenden Untersuchungsergebnisse der verschiedenen Testszenarien werden in diesem Beitrag vorgestellt und kritisch diskutiert.

1 Introduction

In recent years the market of optical 3D sensors has been significantly expanded in the lower (500 Euro to 4,900 Euro), middle (5,000 Euro to 20,000 Euro) and high-end (more than 20,000 Euro) price segment through the development of handheld 3D scanners. The typical application fields of these 3D scanners are mostly limited to close range, i.e. for measuring tasks with distances under one metre up to a few metres. Due to the current technological variety within the area of 3D scanning, it is a challenge to select a suitable scanning system for a specific application. Geometric accuracy investigations of terrestrial laser scanning systems were already published by Kersten et al. (2009), while an accuracy analysis of a handheld mobile laser scanning system for cultural heritage documentation was recently published by Chan et al. (2016).

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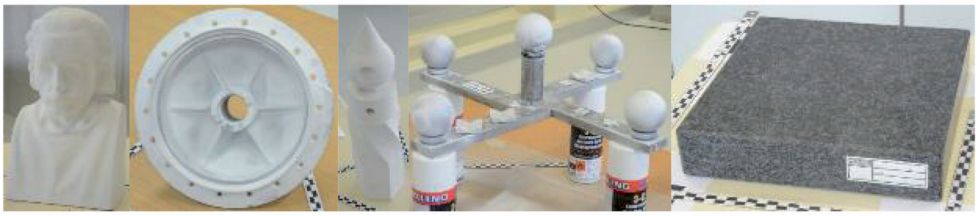


Fig. 1: Reference bodies for the investigations of the handheld scanning systems – from left. Einstein bust, wheel hub, Testy, cross-shaped body HSBO (Bochum) with spheres and granite slab.

Handheld 3D scanners are an optimal supplement to terrestrial laser scanning. However, due to their favourable price and their simple handling these handheld scanners also potentially represent significant competition to the expensive and precise structured light projection systems (also known as fringe projection). Therefore, the question arises, how accurate these 3D scanners are compared to classical structured light systems, e.g. from the manufacturers GOM (2016), Steinbichler (Zeiss 2016) or AICON (AICON3D 2016), and what metric quality the user can expect for the acquired 3D data as a price-to-performance ratio. In this area, some results are already available in the literature, e.g. for systems from the gaming industry as well as so-called low-cost systems (structured light system David SLS-1 and Kinect v1/ReconstructMe) for the 3D reconstruction of small objects (Hieronymus et al. 2011, Wujanz et al. 2011, Khoshelham 2011, Boehm 2014, Kersten et al. 2016a). As expected, these investigations demonstrate that the stability and the metric quality of these systems cannot at present compete with high-end systems.

In the following contribution, geometrical accuracy tests using different handheld 3D scanners (middle price class) will be presented as a continuation of the first tests including low-cost systems such as Structure Sensor, Kinect v1 and v2, and Google´s Project Tango (Kersten et al. 2016b). For these investigations reference datasets that were derived from measurements with high-end structured light systems (AICON smartSCAN and GOM ATOS I 2M) for different stable bodies were used.

2 Reference Bodies

For the benchmarking test the following reference objects were used (Fig. 1): a gypsum bust of Einstein (height of 160 mm), a wheel hub from cast irons with the dimensions 232 × 120 × 232 mm³ and four so-called "Testys" (height of 380 mm) from the Institute for Computer Science of the Humboldt University in Berlin (Reulke & Misgaiski 2012). Further examinations took place using the following geometrically-stable reference bodies from the Bochum University of Applied Sciences (HSBO): a cross-shaped body with steel spheres (max. distance 450 mm of five spheres with a diameter of 65 mm) and a planar granite slab (size 300 × 300 mm²).

3 Tested Handheld 3D Scanning Systems

The following handheld 3D scanning systems (Fig. 2), with selected technical data summarized in Tab. 1, were available for the tests: two DotProduct DPI-7 (State Office of Criminal Investigations Hamburg (LKA), and Dr. Hesse and Partner Engineers, dhp:i), DotProduct DPI-8 (AllTerra Deutschland GmbH, Schenefeld), Artec Spider (LKA, Hamburg), Mantis Vision F5 Short Range (MexConsult, Bredstedt), Creaform HandySCAN 700 (Hanack und Partner, Hamburg).

Fig. 2: Examined handheld scanner systems (from left): DPI-7, DPI-8, Artec Spider, Mantis Vision F5 SR, and Creaform HandySCAN 700.

3.1 *DotProduct DPI-7/DPI-8*

A substantial component of the hardware of the DPI-7 (DotProduct 2016) and DPI-8 scanner (DotProduct, USA) is a PrimeSense sensor (Carmine 1.08/Carmine 1.09), as it is also mounted in the Kinect v1 (NIR projector as well as NIR and RGB cameras). After a cold boot the system needs approximately 20 minutes preheating time. The control of the sensor is carried out by a connected Android tablet using the software Phi.3D. For the registration of the point clouds the sensor data of the internal accelerometers and gyroscopes of the tablet are used. If sufficient overlap is available for the scans (control via visual colour information at the tablet), an ICP algorithm (Besl & McKay 1992) performs a pre-registration of scans. After scanning, the registration will be optimized by also eliminating incorrect points, e.g. mixed pixels. The measuring range of the DPI-7 scanner is between 0.6 m and 3.3 m (0.6 m and 5.0 m for DPI-8 according Trimble's specification), whereby a short range version with up to 1.2 m range (system of dhp:i) and a long range version with up to 3.3 m (systems of the LKA) are available. The instrument has the dimensions of 20 × 24 × 6 cm^3. Investigations of the DPI-7 are presented by Jahraus et al. (2015), applications by Ahern & Spring (2015).

3.2 *Artec Spider*

Artec Spider (Artec3D 2016, Luxembourg) is a handheld 3D scanner, which was developed particularly for CAD users, to scan small items with complex surface structure, sharp edges and thin ribs with 7.5 photos or with 1 million points per second. The system needs a preheating time of approximately 30 minutes and works with a linear field of view between 90 × 70 mm^2 and 180 × 140 mm^2. The measuring range is between 0.17 m – 0.35 m. The Artec Spider uses structured light technolo-

Tab. 1: Selected technical data of the examined 3D scanners (manufacturer's data).

System	Measuring procedure (SL = Structured Light)	Range (m)	Precision (mm)	Weight (kg)	Cost (Euro)
DPI-7 (dhp:i)	SL – speckle pattern	0.60 – 1.20	2 (@ 1m)	< 1.00	5,000
DPI-7 (LKA)	SL – speckle pattern	0.60 – 3.30	2 (@ 1m)	< 1.00	5,000
DPI-8	SL – speckle pattern	0.60 – 5.00	2 (@ 1m)	< 1.00	4,700
Artec Spider	SL – speckle pattern	0.17 – 0.35	0.05	< 1.00	15,700
Mantis F5 SR	SL – speckle pattern	0.30 – 0.80	0.05 (@ 50cm)	0.60	15,000
HandySCAN 700	Stereo-Photogrammetry	0.10 – 4.00	up to 0.03	0.85	49,000
ATOS I 2M	SL – Gray code	0.16 – 1.28	0.02	3.50	50,000
smartSCAN	SL – Gray code	0.03 – 1.50	0.009 (plane)	4.00	80,000

gy (speckle pattern) with blue LED as a light source and a colour camera with 1.3 megapixels (24-bit radiometry) for the texture mapping of the objects. For the generation of 3D models the software Artec studio can be used in combination with the measuring system. Sample applications of this system have been published by Adams et al. (2015), Friedman et al. (2015) as well as Inzerillo et al. (2015).

3.3 *Mantis Vision F5 Short Range*

The Mantis Vision F5 (Israel) is a structured-light handheld scanner with a measuring range of 0.5 m – 4.5 m (MVC F5) respectively 0.3 m – 0.8 m (MV F5 Short Range) (OR3D 2016). The sensor hardware consists of two modules: a video camera and a projector, which is integrated in a grab handle. The projector emits infrared light on the object (proprietary pattern), which is captured as coded light by a video camera. The triangulation algorithm calculates a point cloud with 500,000 points/sec. The point density in XY is 1.6 mm @ 0.5 m distance for each image. The depth of field of the sensor-system is about 0.3 m – 0.8 m. Because of the low sensitivity to the ambient light, the system is usable both in darkness and in daylight. Wrona (2014) and Zhang et al. (2015) describe diverse applications of the scanner.

3.4 *Creaform HandySCAN 700*

The HandySCAN 700 (Creaform 2016) has been introduced as the newest generation of handheld 3D scanning systems from Creaform in May 2014 as "portable 3D measuring solutions and 3D engineering services" (Ametek 2016). Creaform was founded in Lévis, Québec, Canada in May 2002 and is now a part of AMETEK Ultra Precision Technologies. The portable 3D scanner is equipped with power supply, USB 3.0 cable, calibration board, USB stick, positioning targets and a notebook computer with the software *VXelements*. The resolution of the sensor is 0.050 mm, while the scanning area is 275 mm × 250 mm with a depth of field of 250 mm. Two principal cameras, integrated at the front of the sensor on top of each other, acquire 60 images per second. Using seven laser crosses (plus one extra line for difficult accessible areas) as a light source, the system is able to provide 480,000 measurements per second to generate the point cloud for 3D meshing. The sensor position is determined in real-time by spatial resection using retro-reflective targets in object space. Ouimet et al. (2015) present the use of the former system HandySCAN 3D for the documentation of masonry sculptural elements of the Canadian Parliament Buildings. Starosta (2016) investigated the operational capability of the 3D scanner HandySCAN 700.

3.5 *Reference systems – ATOS I 2M and AICON smartSCAN 3D*

The GOM (Company for Optical Measuring Technology) ATOS (Advanced Topometric Sensor) I 2M, Braunschweig, Germany, is a structured light projection system (Gray code/phase shift) consisting of two CCD cameras having 1624 × 1236 pixels each and a structured light projector. Depending on the lenses used the field of view varies between 500 × 400 mm^2 and 250 × 200 mm^2. The ATOS I 2M had been employed as a measuring and reference system in different applications (Kersten et al. 2012, Rau & Yeh 2012, Kersten & Lindstaedt 2012, Kersten et al. 2016a).

The smartSCAN 3D from AICON 3D Systems GmbH, Braunschweig, Germany, is a structured light projection system (white light scanner), which operates with the combined gray-code/phase-shift technology. The cameras (in this case delivering 5 Megapixel) record the structured-light pattern (light source: white LED, alternatively green, blue or red) under a predefined triangulation angle, with a measuring sequence of one second. The scanner works in a measuring range from 30 mm to 1500 mm. Examples of use are presented by Slizewski et al. (2010) and Bathow & Breuckmann (2011).

4 Data Acquisition

The measurements took place on the 5th and 6th of January and 6th of July 2016 in the Geomatics lab at the HafenCity University Hamburg. At various stations data of the reference bodies had been derived from handheld 3D scanners, cameras and the two reference systems. For the wheel hub and the cross-shaped HSBO test body a coating spray was used to convert the shiny surface into a matt and bright surface.

For data acquisition all handheld scanners have to be moved manually, in a slow and uniform movement, around the whole object in a distance between 20 cm and 50 cm. The collected data is transferred to the connected tablet (DPI-7/DPI-8, Mantis F5) or computer (Artec Spider, HandySCAN 700) in real time and displayed in the software. Normally the instruments are used in one go, after having passed through the usual warm-up phase. No turning off occurred during the measurements of a specified reference body, although some of the sensors, e.g. DotProduct DPI, take a short break (less than 1 minute for an additional warm-up of the camera) when beginning a new imaging session. Fast or abrupt movements should be avoided because they will lead to a loss of the continuous automatic registration. Should such an interruption occur, it can be handled in the software in different ways. For instance, the DPI-7 and the DPI-8 have to be moved again over a part of the object that has already been captured for re-orientation. The Mantis Vision F5 control unit only shows the current video image and not the captured data, so a possible loss of signal can only be repaired by registration of segments in post processing. The experience of the operator influences the speed and quality of data collection significantly. The manual movements of the sensor have to be coordinated with the live-view on the display. The acquisition time is a few minutes for all scanners, depending on the object complexity; two of the systems need a preheating time first (Artec Spider and DPI-7/DPI-8).

For the measurements with the structured light projection systems ATOS I 2M and smartSCAN the objects were placed on turntables. The systems were calibrated before the recording started. The data collection is done in a number of single scans, which are registered to each other by using small targets stuck onto the object (ATOS) or matching aids (small, explicit geometrically structured objects), which are placed in object space (smartSCAN). For the ATOS system the number of scans per object lay between 24 and 120 with the registration accuracy differing between 0.023 mm and 0.041 mm. Generally, the number of scans differs, depending on the size, shape and overall complexity of the object. To measure the HSBO cross-shaped body, 70 scans had to be acquired using the smartSCAN, while the acquisition of the granite slab could be completed with only 10 scans.

5 Evaluation and Results

To evaluate the data from the diverse measurement systems multiple formats had to be processed. Some systems delivered point clouds (DPI-7/DPI-8), some others already generated 3D models on the fly by triangulating meshes using the system software (Mantis F5, Artec Spider, HandySCAN 700, ATOS, smartSCAN).

Three reference bodies (Testy, wheel hub and a bust of Einstein) were measured in detail and at high precision with the fringe projection systems and afterwards the meshing was carried out using Geomagic Studio 2012 (Geomagic 2016). The ATOS system generated the reference datasets for Testy 1, 2 and 3, while Testy 4, the wheel hub and the bust of Einstein were measured with the smartSCAN.

The guideline VDI/VDE 2634, part 2 and 3, is an accredited standard for acceptance tests (verifying the specified accuracy) and reverification (to ensure long-term compliance) of optical measurement systems based on area scanning (VDI/VDE 2002, 2006). Using the framework of well-defined test scenarios, suitable test objects (artefacts) are employed to determine quality parameters. Following the guidelines, tests were executed using the cross-shaped body HSBO with spheres and the granite slab. The derivable quality parameters are:

- Probing error PS (size): This quality parameter arises from the difference between the measured diameter and the diameter of the calibrated sphere.
- Probing error PF (shape): This quality parameter is the range of the radial dis-

tance between the measured points and a best-fit sphere. The best-fit sphere is determined according to the least-squares method with free radius.

- The sphere-spacing error SD is determined from the difference between the measured and calibrated values of the distance between the centres of two spheres. The measured distance is derived from the measured values obtained from multiple area-based probings. The limit, SD, for the permissible three-dimensional sphere-spacing error is the quality parameter sphere-spacing error. It is determined as a length-independent quantity and shall be observed within the entire measuring volume specified.
- The quality parameter flatness measurement error, RE, is the range of the signed distances of the measurement point from the best-fit plane calculated according to the least-squares method.

To evaluate the datasets and calculate the quality parameters Geomagic Studio was used.

5.1 *Cross-shaped Reference Body HSBO with Spheres*

Fig. 3 shows the probing errors (PS and PF) determined for the HSBO reference body. The characteristic curves of the reference system smartSCAN refer to a comparative measurement with a laser tracker API T3 (interferometric measurement accuracy: > ±15 µm or 1.5 ppm), while the other graphs are referenced to the smartSCAN system. Related to the probing error PS (Fig. 3 left) it is remarkable that some sensors (DPI-7, DPI-8, Mantis F5) point out systematic deviations: measurements are too large or too small. Therefore, it can be assumed that the systems have scale problems from the sensor calibration. Compared to the reference system the probing error PS of these systems is larger by a factor of about 5 – 35. The best results in this test have been achieved by the HandySCAN 700, reaching almost the accuracy of the reference system.

The probing error PF (Fig. 3 right) shows the noise behaviour of the sensors. The results of the two DPI-7 handheld scanners are homogeneous and oscillate around 10 mm, while the DPI-8 as the follow-up system shows a significant improvement possibly due to data filtering. With the Mantis F5 scanner this value is below 2 mm on average. The Creaform HandySCAN 700 shows again the best results, compared to the reference system.

The sphere-spacing errors (Fig. 4) show systematic positive or negative deviations for almost all sensors. These effects are particularly pronounced with the Mantis F5 as well as with the DPI-7 (on the average approx. 1% of the distance). The afore-mentioned scale error is to be assumed as the main reason for this behaviour. The DPI-8 shows a slight im-

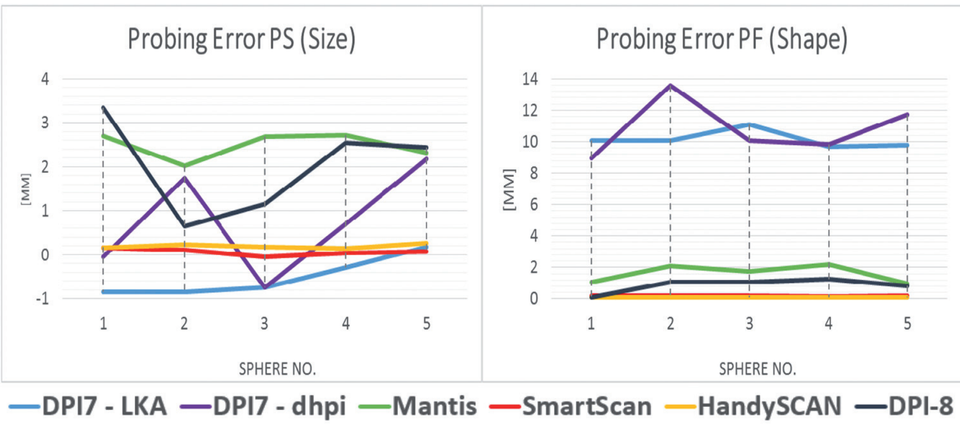


Fig. 3: Quality parameter probing error (PS / PF) equivalent to VDI/VDE 2634, part 3.

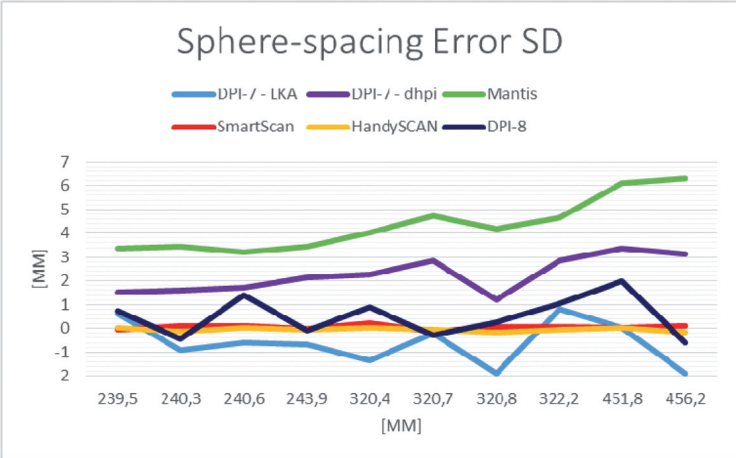


Fig. 4: Quality parameter sphere-spacing error (SD) equivalent to VDI/VDE 2634, part 3 for the distances between the spheres (x-axis).

provement compared to the DPI-7. This test procedure also shows the high quality of the Creaform sensor HandySCAN 700, the results of which are absolute comparable to those achieved by the fringe projection system.

5.2 *Reference Body Granite Slab*

The charts of Fig. 5 show the results of the flatness measurement error RE for the reference body "granite slab". A dependence between the arrangement of the object surface (granite slab with a coincidental pattern, consisting of bright and dark areas) and the measurement principle of the particular sensor is also visible here. It is recognizable from the data of the structured light projectors (smartSCAN and ATOS) that both systems are able to measure the surface with a similar quality, although the number of acquired points differs significantly. It might be assumed that one reason for this lies in the different principles of the scanners' projector units, a current LED lighting with the smartSCAN respectively halogen light with the ATOS, while another reason might be the different resolutions of the cameras.

The granite slabs measured by photo triangulation with the HandySCAN 700 shows a flatness measurement error which is comparable to the results of the structured-light projectors. The natural texture of the granite slab here surely meets the requirements of stereo-photogrammetry. Systems with active projection are disadvantaged in this case. An interesting effect also can be seen with the DPI-7 and DPI-8 scanners: obviously there is no direct dependance between the number of points in the cloud and the surface quality.

5.3 *Reference Body Testy*

The results of the 3D comparisons between the systems tested and reference system (ATOS) are summarized in Tab. 2 and illustrated in Fig. 6. The 3D comparison of the two reference systems (ATOS and smartSCAN) shows very small average deviations of less than 10 µm, and even the span, which is calculated from the difference between the average negative and positive deviations, is very low (approximately 30 µm). Thus, the good quality of this two structured light projection systems is confirmed as a reference system with superior accuracy. However, the best result has been achieved with the HandySCAN 700, since the deviation to the reference is in the range of the smartSCAN. No other handheld 3D scanner could achieve these accuracies. Furthermore, some other systems (DPI-7, DPI-8 and Artec Spider) could not completely capture the Testy

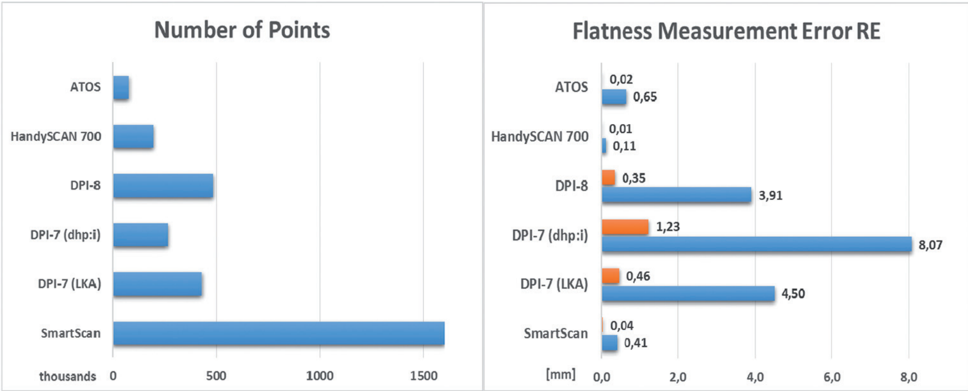


Fig. 5: Quality parameter flatness measurement error (RE) equivalent to VDI/VDE 2634, part 2. Right fig.: BLUE – flatness measurement error, ORANGE: standard deviation (mm).

due to the complex geometry and all handheld structure light systems showed obvious systematic scale differences (Fig. 6).

5.4 *Reference Body Einstein Bust*

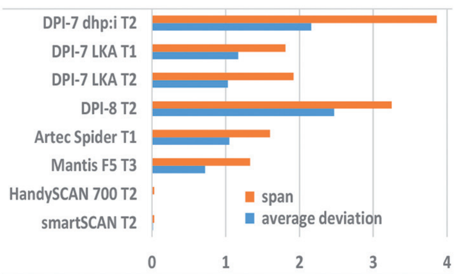
The results of the 3D comparisons with the Einstein bust are summarized in Tab. 3 and presented in Fig. 7 in colour. The best numerical and visual result is reached by the HandySCAN 700. From the DPI 7/DPI-8 and the Artec Spider data, only models containing big holes could be created. The high deviations in the DPI-7/DPI-8 data show that they cannot cope with the homogeneous white surface of the Einstein bust. For this object the two higher-assessed systems, Mantis F5 and Artec Spider, could not achieve the specifications quoted by the manufacturer in these tests.

5.5 *Reference Body Wheel Hub*

The most complex and difficult reference body concerning this investigation is the wheel hub. Due to its symmetry, it can only be aligned clearly using a few small parts of the object, a grooved profile on the back and some elevated letters inside. If these parts were not visible in the data (e.g. of the DPI-7 LKA) due to low scan resolution, the object could not be aligned and compared to the reference object. With the exception of the HandySCAN 700 none of the investigated systems could generate a complete model if the wheel hub was taken only from one position and not rotated. The 3D models from DPI-7/DPI-8 and from Artec Spider were not useful, since visually unacceptable models were generated. The final 3D models and the colour-coded differences between test data and reference mod-

Tab. 2: Average deviations (Ø dev.) (mm) of the Testys – 3D comparison in Geomagic between reference (ATOS, # of triangles ca. 250.000) and test system, T = Testy, Sp = span.

System	# triangles	Ø dev.	Sp
A: DPI-7 dhp:i | T2	588,221	2.16	3.86
B: DPI-7 LKA | T1	466,114	1.17	1.81
C: DPI-7 LKA | T2	448,993	1.03	1.92
D: DPI-8 | T2	452,086	2.47	3.25
E: Artec Spi. | T1	2,621,776	-1.05	1.60
F: Mantis F5 | T3	4,371,360	0.72	1.33
G: HandySC. | T2	1,236,568	0.01	0.03
H: smartSC. | T2	1,156,735	-0.01	0.03



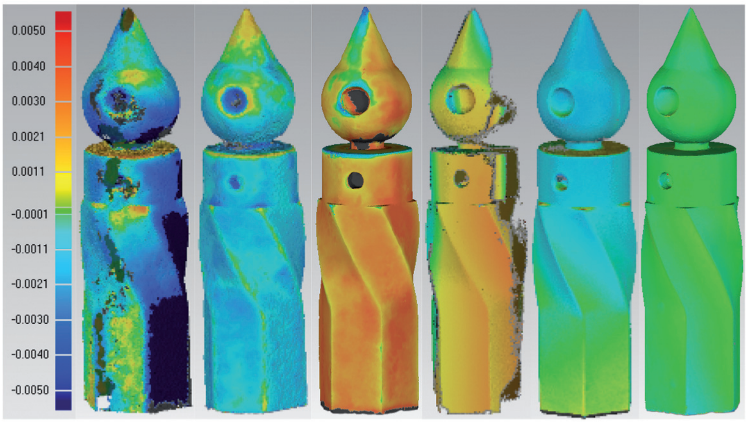


Fig. 6: Deviations (m) of the different Testys (3D comparison in Geomagic test data vs. reference) (from left to right) – DPI-7 dhp:i T2 (A), DPI-7 LKA T1 (B), DPI-8 T2 (D), Artec Spider T1 (E), Mantis F5 T3 (F) and HandySCAN 700 T2 (G).

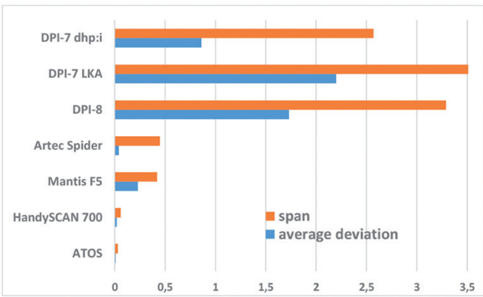
el are shown in Fig. 8. This shows that the HandySCAN 700 delivered the best numerical and optical results. The visual impression is also confirmed by the results in Tab. 4, i.e. the HandySCAN 700 and the structured light projection system ATOS (here used for comparison) have the smallest average deviations. By contrast to this, the Mantis F5 shows significant systematic effects which might be caused by false scaling from system calibration. Mantis F5 and Artec Spider could not achieve the manufacturer's accuracy specifications. The other systems achieve the specified accuracy, but they are rather unsuitable for this technical application due to the optical quality of the generated model.

6 Conclusion and Outlook

In this contribution the results of the comparative geometrical accuracy tests for different handheld 3D scanners were presented. The tests demonstrated that the evaluated middle class scanning systems currently do not reach the accuracies and the quality of the reference data produced by high-end structured light systems. The Creaform HandySCAN 700 is an exception, since the results of this high-end system are very close to the reference systems, i.e. it is a portable and flexible 3D scanner with almost the same accuracy as static structure light systems. However, it should be noted that not all of the selected reference bodies corresponded optimally to the typical range of applications of the tested 3D scanners. In principle, the handling of these systems is simple.

Tab. 3: Average deviations (Ø dev.) (mm) of the Einstein bust – 3D comparison in Geomagic between reference (smartSCAN, # of triangles 1,110,302) and test system, Sp = span.

System	#triangles	Ø dev.	Sp
A: DPI-7 dhp:i	175,696	0.86	2.57
B: DPI-7 LKA	167,556	2.20	3.53
C: DPI-8	497,978	1.73	3.29
D: Artec Spider	1,299,298	0.04	0.45
E: Mantis F5	8,089,764	0.23	0.42
F: HandySCAN	1,100,302	0.02	0.06
G: ATOS	769,262	0.01	0.03



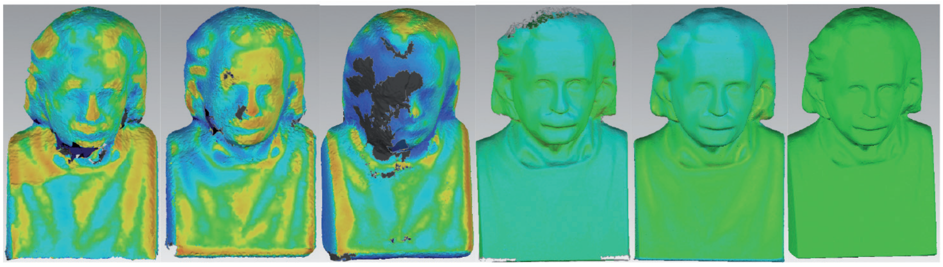


Fig. 7: Deviations (m) of the different Einstein busts (3D comparison in Geomagic test data vs. reference) (from left to right) – DPI-7 dhp:I (A), DPI-7 LKA (B), DPI-8 (C), Artec Spider (D), Mantis F5 (E) and HandySCAN 700 (F). Scale identical to Fig. 6: green 0.1 mm, red +5 mm, blue -5 mm.

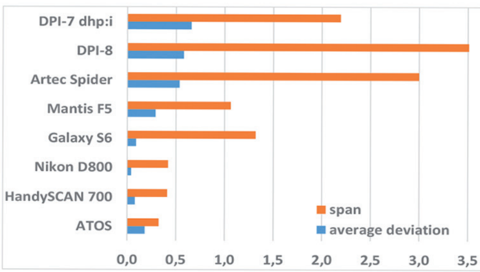
However, the scanning by slow, homogeneous movements – around and over the object to be recorded – requires appropriate user experience for keeping a permanent matching between the scanned point clouds. The acquisition speed of a few minutes for each object is quite high for all presented systems.

Following the guideline of VDI/VDE 2634, part 2 and 3, the determined quality parameters (probing error and sphere-spacing error) gave a clear indication that the instrument scale was not precisely determined for some handheld scanners and/or that the sensor is possibly not stable due to a mechanically unstable structure. Procedures for the field check and/or simple self-calibration achievable by any user are therefore both meaningful and necessary. The result of the flatness measurement error tests document that the image-based acquisition procedure with the HandySCAN 700 has very small deviations compared to the structured light systems, while the systems with active projection show deviations that are larger than those of the reference systems by a factor of 8-50. It can be concluded that the signal to noise ratio of the active scanning systems needs significant improvements. Comparing the latest DotProduct systems, the DPI-8 provides an improvement with respect to the DPI-7 only in the tests concerning the guideline VDI/VDE 2634.

The two systems Mantis F5 and Artec Spider settled in the middle price segment could not satisfy the accuracy specifications of their manufacturers in the investigations using the reference bodies Testy, wheel hub and Einstein bust. However, beside the pure accuracy values (average deviation and span), the visual quality and the completeness of the scanned test objects must also be considered as a criterion for the evaluation of the entire quality of an examined system. The visual quality of the models was better with the Mantis F5 than with the other handheld scanners. Using the data of the DPI-7/DPI-8 and the Artec Spider, no satisfying models of the reference bodies could be generated due to many holes in the dataset and noise of the point clouds.

Tab. 4: Average deviations (Ø dev.) (mm) of the wheel hub – 3D comparison in Geomagic between reference (smartSCAN, # of triangles 6,352,367) and test system, Sp = span.

System	# triangles	Ø dev.	Sp
A: DPI-7 dhp:i	454,234	0.66	2.19
B: DPI-8	436,625	0.58	3.56
C: Artec Spider	1,193,774	0.54	3.00
D: Mantis F5	5,494,803	0.29	1.06
E: HandySCAN	7,257,962	0.08	0.41
F: ATOS	642,677	-0.18	0.33



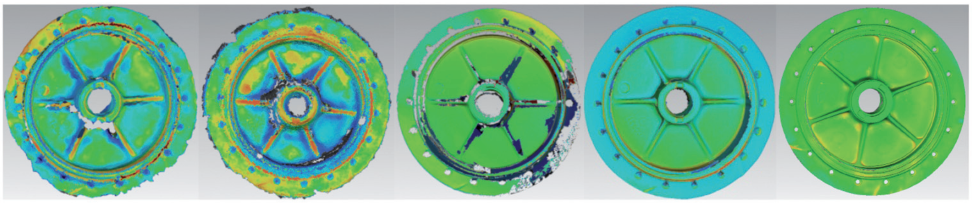


Fig. 8: Deviations (m) of different wheel hubs (3D comparison in Geomagic test data vs. reference) (from left to right) – DPI-7 dhp:i (A), DPI-8 (B), Artec Spider (C), Mantis F5 (D) and Handy-SCAN 700 (E). Scale identical to Fig. 6: green 0.1 mm, red +5 mm, blue -5 mm.

Although it is not documented in these investigations, it was also noticed that the quality of a model generated with a specific system has a strong dependence on the experience of the operator. Future investigations should be carried out in the context of alternative test scenarios, e.g. with larger reference bodies. Moreover, using those reference bodies and a test field a comparison with laser scanner measurements seems to also be meaningful, as generally the handheld systems will be able to fill a gap between high precision structured light systems (in comparison to high-end and middle class handheld 3D scanners) and terrestrial laser scanners (in comparison to low-cost handheld 3D scanners).

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