The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-2/W8-2024
8th International ISPRS Workshop LowCost 3D - Sensors, Algorithms, Applications, 12–13 December 2024, Brescia, Italy

Geometric Accuracy Investigations of Mobile Phone Devices in the Laboratory Using High-Precision Reference Bodies

Thomas P. Kersten[1], Lennart Sönksen[1] & Heinz-Jürgen Przybilla[2]

[1] HafenCity University Hamburg, Photogrammetry & Laser Scanning Lab
Henning-Voscherau-Platz 1, D-20457 Hamburg, Germany
[Thomas.Kersten, Lennart.Soenksen]@hcu-hamburg.de

[2] former Bochum University of Applied Sciences, heinz-juergen@przybilla.biz

Keywords: 3D, accuracy, comparison, dense point cloud, meshed model, reference data, smartphone.

Abstract

The sensors in modern mobile phones (running either the Android or iOS operating system) have become increasingly sophisticated, to the extent that they can be used as measuring systems for a wide range of applications. On the one hand, GNSS (Global Navigation Satellite Systems) and IMU (Inertial Measurement Unit) provide precise positioning of smartphone sensors. On the other hand, the in-built cameras offer an increasingly high geometric image resolution. In order to investigate the potential of mobile phones for creating 3D models of small objects for the documentation of museum artefacts, the Laboratory for Photogrammetry & Laser Scanning of the HafenCity University Hamburg tested various smartphones for geometric accuracy under laboratory conditions. Four Galaxy S-series smartphones of Samsung (S21+, S22, S23, S24 Ultra) and two Apple iPhones (13 Pro and 15 Pro Max) were used for the tests. The image data sets of three distinct test objects, captured with disparate mobile devices, were processed in Agisoft Metashape into 3D models by triangle meshing and subsequently compared with highly accurate reference data from an ATOS 5 structure-light projection system. Some selected examples of image data sets recorded with the iPhone 15 Pro Max were also processed in the Polycam app. The results of the geometric accuracy analyses demonstrated that the image data captured by smartphone cameras could be processed into highly accurate three-dimensional models of the objects. The deviations from the reference data were only marginally inferior to those observed in the models generated from image data obtained from a SLR camera.

1. Introduction

Smartphones utilising the iOS (iPhones) and Android operating systems, which incorporate mapping functionality, have been commercially available for a number of years. To what extent, then, can such mobile systems already be used as professional mapping tools? In addition to increasingly powerful cameras, current smartphones have a plethora of important sensors and functions that can be utilised as 3D recording systems and mapping tools. For data acquisition, a smartphone usually has two to three cameras, a GNSS sensor, acceleration sensors and gyroscopes for positioning the system in 3D space. In addition, a smartphone has a magnetometer which displays the orientation or north direction by a compass, as well as a barometer for measuring altitude (Kersten, 2020). Current-generation smartphones have built-in RGB cameras of up to 200 MP (e.g. the Samsung Galaxy S24 Ultra) to take high-resolution photos. The range of apps for generating 3D objects is also expanding at a rapid pace. However, the suitability of these systems for professional use with an appropriate level of accuracy is contingent upon not only the built-in sensors, but also the available computing power, RAM and data storage capacity, as well as possibilities for cloud computing within the smartphone apps. The performance of current smartphone generations has also led to a notable expansion in the range of sophisticated software applications (APPs). As applications from the gaming industry, virtual reality and also classic engineering are increasingly smartphone-based, this also affects the availability of 3D-oriented APPs. The advent of high-resolution cameras and LiDAR sensors (in the iPhone 12) has enabled the capture and generation of 3D objects on a mesh basis.

The Laboratory for Photogrammetry & Laser Scanning at HafenCity University (HCU) Hamburg has conducted a series of geometric accuracy analyses on a range of smartphones (IOS and Android based). In these analyses, the cameras of the mobile phone devices and, when available, the LiDAR sensor of the iPhone were employed for the acquisition of data from small objects. The Agisoft Metashape software was employed to generate three-dimensional point clouds and mesh three-dimensional models from the image data, while the LiDAR data was already available in the form of three-dimensional point clouds, in this case processed using the Polycam app (Polycam, 2024). In order to scale the point clouds and the Polycam meshes, various photogrammetrically calibrated scale bars were placed in object space during the image acquisition.

2. Related Work

Mobile devices, including different kinds of smartphones, have been utilised as surveying instruments for a considerable period of time. Tanskanen et al. (2013) present a comprehensive on-device 3D reconstruction solution for mobile monocular hand-held devices. This innovative approach generates dense 3D models with absolute scale on-site, while simultaneously providing users with real-time interactive feedback. Bakuła and Flasiński (2013) conducted an evaluation of the capacity of a smartphone to generate a georeferenced photorealistic 3D model. The model was created using point clouds generated from stereoscopic photographs. Masiero et al. (2016) employed a low-cost mobile device (a smartphone manufactured by Huawei, model number Sonic U8650) in order to develop an indoor mobile mapping system. Yilmazturk and Gurbak (2019) conducted geometric analyses of mobile phone camera images

https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-211-2024 |

captured by a Samsung Galaxy S4 in order to derive 3D information. This was achieved through the utilisation of a self-calibration bundle block adjustment, as well as the generation of a 3D mesh model of a historical cylindrical structure (height = 8 m and diameter = 5 m) through a Structure-from-Motion and Multi-View-Stereo (SfM-MVS) approach. In their study, Saif and Alshibani (2022) evaluated the potential of smartphones as data acquisition tools in comparison with compact cameras. This was based on the quality and accuracy of their photogrammetric results in extracting geometrical measurements (i.e. surface area and volume) for construction management applications.

In a recent study, Luetzenburg et al. (2021) evaluated the potential of the Apple iPhone 12 Pro LiDAR for use in geosciences. The LiDAR sensors produced precise, high-resolution models of small objects with a side length exceeding 10 cm, with an absolute accuracy of ±1 cm. Additionally, 3D models encompassing dimensions of up to 130×15×10 m of a coastal cliff in Denmark were compiled with an absolute accuracy of ±10 cm. Another application in geology was employed by Fang et al. (2021) using a multi-smartphone measurement system in slope model tests. That smartphones could be used in medical applications has been demonstrated by Quispe-Enriquez et al. (2023) in a smartphone photogrammetric assessment for head measurements using three smartphone models (Samsung Galaxy S22 Ultra, S22, and S22+).

The research conducted by Elias et al. (2020) examines the impact of temperature fluctuations on the geometric stability of smartphones and Raspberry Pi cameras. Additionally, Elias et al. (2019) employed smartphone technology for the purpose of photogrammetric water level determination.

This contribution presents the findings of an investigation into the geometric accuracy of a number of Android smartphones and iPhones (see section 3). The objective was to evaluate these devices for their suitability to calculate mesh models for the documentation of small objects in cultural heritage applications used by museums.

3. Mobile Phone Devices Used

The technical specifications of mobile phone devices used for geometric accuracy investigations are summarised in Table 1. In total, four Galaxy S-series smartphones of Samsung (S21+, S22, S23, S24 Ultra) and two Apple iPhones (13 Pro and 15 Pro Max) were used for the tests, while the iPhone 15 Pro Max is equipped with a Sony IMX 803 camera (Fagot, 2023) and a Digital Flash LiDAR (Zhang et al., 2019), which was used for the investigations. For comparison, all objects were also photographed with a Nikon D7500 DSLR camera (focal length c = 35 mm, 20 megapixels (MP)).

4. Reference Bodies

For the benchmarking test the following reference objects were used (Figure 1): a bust of Einstein from gypsum (height of 160 mm), a Moai figure from Easter Island (height 140 mm) and a so-called “Testy” (height of 380 mm) from the Institute for Computer Science of the Humboldt University in Berlin (Reulke & Misgaiski, 2012) and a planar granite slab (size 300×300 mm²). For purposes of comparison, all three figures were scanned by a high-precision structured-light system, ATOS 5, developed by Carl Zeiss GOM Metrology. The system is designed for high-speed 3D scanning, rapid data processing, and higher resolution (Carl Zeiss GOM Metrology, 2024). The ATOS 5 employs an LED as a light source, has a measuring area of 170×140 – 1000×800 mm, a working distance of 880 mm, and is capable of measuring up to 12 million points per scan. The two reference bodies, Testy and Einstein's bust, and the granite slab have already been used to analyse the geometric accuracy of handheld 3D scanners (Kersten et al., 2016a & 2016b; Kersten et al., 2018), while the Testy and Einstein bust have also been used to analyse the geometric accuracy of low-cost systems (Kersten et al., 2016a; Kersten et al., 2024).

Device/ Parameter	Galaxy S21+	Galaxy S22	Galaxy S23	Galaxy S24 Ultra	iPhone 13 Pro	iPhone 15 Pro Max
Camera MP	12/64/10	12/50/10	12/50/10	12/50/200	12/12	48/12/12
Pixel size	0.8 µm (64)	1.4 µm (12)	1.0 µm (50)	0.6 µm (200)	1.9 µm (12)	1.22 µm (48)
# Pixel used	6936 × 9248	3000 × 4000	8160 × 6120	12240 × 16320	3024 × 4032	6048 × 8064
Focal length	5.4/5.9 mm	5.4 mm	5.4 mm	6.3 mm	5.7 mm	6.76 mm
F-Stop	1.8/2.0	1.8	1.8	1.7	1.8	1.78
RAM	8 GB	8 GB	8 GB	8/12 GB	6 GB	8 GB
Storage MB	128/256	128	128/256	256/512	128-1000	256-1000
Weight	200 g	168 g	167 g	233 g	203 g	221 g

Table 1. Technical specification of the mobile phone devices used for the geometric accuracy investigations.

Figure 1. Reference bodies for the benchmarking test (f.l.t.r.) – Einstein bust, Moai figure, Testy, and planar granite slab.

Device/ Object	Galaxy S21+ (64 MP)	Galaxy S21+ (12 MP)	Galaxy S22 (12 MP)	Galaxy S23 (48 MP)	Galaxy S24 Ultra (200 MP)	iPhone 13 Pro (12 MP)	iPhone 15 Pro Max (24 MP)	iPhone 15 Pro Max (48 MP)
Testy	102	115	193	135	209	257	231	221
Moai	-	-	153	72/65	66/56	-	-	65/95
Einstein	110	169	113	132	93	122	-	-
slab	121	167	152	191	47	175	-	78

Table 2. Number of photos taken using different mobile phones with different image resolutions (MP = megapixels).

5. Data Acquisition

The acquisition of photographs with the different mobile phone devices were carried out in June and in October 2024 in the Photogrammetry & Laser Scanning Lab of HafenCity University Hamburg. Nevertheless, as illustrated in Table 2, not all objects could be captured by all mobile phones. It is regrettable that the recording conditions in the laboratory were not optimal, as the large window on the front side of the room allowed a considerable amount of light to enter, which had a slight impact on the recorded data. The reference scans were already conducted during a practical exercise for students in January 2024 using the structured-light system ATOS 5 supported by the engineering office GDV Systems + Solutions GmbH in Bad Schwartau, Germany.

To acquire the image data, all mobile phones were moved around the entire object at a distance of between 10 cm and 100 cm in order to capture a sequence of images from different perspectives. The structure of the object is illustrated in Figure 2, which shows the calibrated scale bars that were placed around the object to scale the image data and the 3D model to be created. The photographs were taken by three operators with different photogrammetric experiences. In Table 2 the number of photos taken using different mobile phones with different image resolutions are summarized. The Moai figure was photographed from two distinct perspectives, with the figure being rotated upside down for the second set of images. Consequently, a complete 3D model without a hole at the bottom of the figure can be calculated from the two data sets.

Additionally, the iPhone 15 Pro Max captured images of the Testy for subsequent processing in Polycam. However, it is currently not possible for Polycam to process images captured on the iPhone with a resolution of 48 megapixels at the full resolution. Despite the advent of newer iPhone models, such as the iPhone 14 Pro and iPhone 15 Pro, which are capable of capturing 48-megapixel images, these high-resolution photos are reduced to a lower resolution in Polycam for the purposes of more efficient processing and enhanced memory management. According to Polycam (2024), the app uses the standard resolution (12 MP) of the iPhone camera, as this provides sufficient detail for photogrammetry while simultaneously reducing the hardware requirements for 3D modelling.

The initial results obtained from the Apple LiDAR were unsuccessful, and it was not possible to ascertain the correct utilisation of the measuring system. Consequently, no useful recordings were made with this system. It is therefore necessary to conduct further investigations with the measuring system at a later date.

6. Data Evaluation and Results

All image data sets from the various mobile phone cameras were processed using Agisoft Metashape V2.0 software. Following the import of the image data, a sparse point cloud was generated in order to calculate the image orientations and camera calibrations. In order to calibrate the camera, the following parameters were determined through the bundle adjustment: camera constant c (focal length), principal point (x_0, y_0), radial-symmetric distortion (k_1, k_2), tangential distortion (p_1, p_2), affinity and shear (b_1, b_2). Subsequently, the points on up to six scale bars were automatically measured in each images data set, after which the respective scale was specified manually in millimetres. This was used to scale the image blocks.

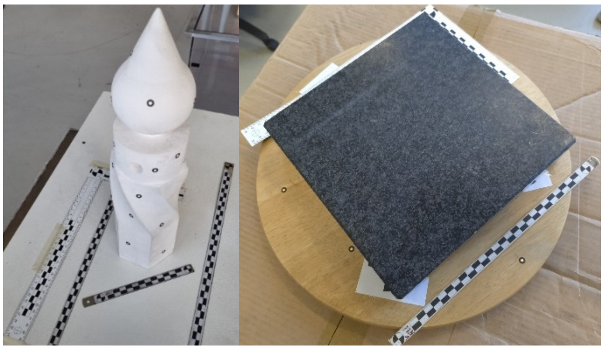

Figure 2. Structure of the recording object with calibrated scale bars around it for scaling the image data and the 3D model to be created.

The following scale bars were placed in object space (Figure 2): three steel scale bars calibrated by photogrammetric bundle adjustment with the length of 47 cm, 28 cm and 13 cm, while on additional scale with 37 cm was on the longest scale bar with 47 cm. Two additional scale bars of 13 cm and 15 cm were available on paper as a triangle. The average deviations of the scales for

Objects	Nikon D7500 (20 MP)	Galaxy S21+ (64 MP)	Galaxy S22 (12 MP)	Galaxy S23 (48 MP)	Galaxy S24 Ultra (200 MP)	iPhone 13 Pro (12 MP)	iPhone 15 Pro Max (24 MP)	iPhone 15 Pro Max (48 MP)
Testy	0.37 mm	0.50 mm	0.37 mm	0.37 mm	0.30 mm	0.38 mm	0.31 mm	0.38 mm
Moai	0.36 mm	-	0.95 mm	2.82 mm	0.57 mm	-	0.93 mm	-
Einstein	0.33 mm	0.66 mm	0.62 mm	-	0.62 mm	0.32 mm	-	-
Slab	0.41 mm	0.56 mm	0.30 mm	0.30 mm	0.66 mm	0.69 mm	0.52 mm	-

Table 3. Average deviations at the scale bars after bundle block adjustment in Agisoft Metashape.

Mobile Phone	Object	# triangles	Ø deviation [mm]	Std. dev. [mm]	Ø Span [mm]
Nikon D7500	Testy	149 568	+0.28 -0.27	0.87	0.55
Galaxy S21+ (64 MP)	Testy	305 216	+0.60 -0.75	1.29	1.35
Galaxy S22 (12 MP)	Testy	118 456	+0.37 -0.47	1.17	0.84
Galaxy S23 (48 MP)	Testy	567 289	+0.31 -0.40	1.18	0.71
Galaxy S24 Ultra (200 MP)	Testy	1 961 843	+0.47 -0.96	2.00	1.43
iPhone 13 Pro (12 MP)	Testy	87 213	+0.25 -0.25	0.80	0.50
iPhone 15 Pro Max (24 MP)	Testy	79 959	+0.22 -0.21	0.86	0.43
iPhone 15 Pro Max (48 MP)	Testy	183 172	+0.32 -0.46	1.13	0.78
Nikon D7500	Moai	46 090	+0.17 -0.05	0.15	0.22
Galaxy S22 (12 MP)	Moai	207 211	+0.39 -0.19	0.43	0.58
Galaxy S23 (48 MP)	Moai	274 828	+0.36 -0.25	0.56	0.61
Galaxy S24 Ultra (200 MP)	Moai	1 661 650	+0.46 -0.65	1.03	1.11
iPhone 15 Pro Max (48 MP)	Moai	145 277	+0.08 -0.04	0.10	0.12
Nikon D7500	Einstein	90 790	+0.12 -0.23	0.60	0.35
Galaxy S21+ (64 MP)	Einstein	480 938	+0.16 -0.34	0.66	0.50
Galaxy S22 (12 MP)	Einstein	132 377	+0.22 -0.35	0.65	0.57
Galaxy S24 Ultra (200 MP)	Einstein	2 227 344	+0.26 -0.37	0.59	0.63
iPhone 13 Pro (12 MP)	Einstein	143 679	+0.12 -0.21	0.59	0.33
Nikon D7500	Slab	76 268	+0.05 -0.03	0.05	0.08
Galaxy S21+ (64 MP)	Slab	1 377 286	+0.07 -0.07	0.09	0.14
Galaxy S22 (12 MP)	Slab	294 367	+0.12 -0.06	0.13	0.18
Galaxy S23 (48 MP)	Slab	1 578 550	+0.14 -0.11	0.16	0.25
Galaxy S24 Ultra (200 MP)	Slab	376 352	+0.04 -0.05	0.06	0.09
iPhone 13 Pro (12 MP)	Slab	292 254	+0.03 -0.03	0.04	0.06
iPhone 15 Pro Max (24 MP)	Slab	219 455	+0.05 -0.04	0.06	0.09

Table 4. Results of the 3D deviation analyses using Geomagic Wrap.

each data sets achieved after bundle block adjustment are summarised in Table 3. The mean discrepancies at the scales for the most image data sets were within the range of 0.3 mm to 0.95 mm, which is also contingent upon the image quality of the data sets (sometimes inadequate depth of sharpness). However, the mean deviations at the scales exceeded 1 mm for one image data sets: the Moai figure with the Galaxy S23. When calculating the 3D model of the Moai figure, two image data sets (chunks) were combined in Metashape, which could have contributed to the elevated mean deviation of 2.8 mm. The geometric mean of the deviation is slightly higher for this Galaxy 23 data set than the other results (Table 4), and systematic effects are evident at the base of the 3D model (Figure 5).

Once the photographs had been orientated and the respective camera calibrated, a dense point cloud was calculated in Metashape using the medium setting. As special case, the two respective image data sets of the Moai were previously brought together using masks of the cleaned sparse point clouds of the figure. The dense point clouds were then cleaned up so that only a point cloud of the object was obtained. Finally, a triangular meshing and texturing could be calculated using this cleaned dense point cloud. The textured 3D models were exported as OBJ files and imported into Geomagic Wrap for a 3D comparison with the models of the reference bodies. Prior to the 3D comparison, the two data sets to be compared were registered with each other. The results of the 3D comparison are presented in Table 4 and illustrated in the subsequent figures for each object. Table 4 presents the number of triangles, the mean positive and negative deviations, the standard deviation, and the span, which is calculated as the sum (absolute value) of the mean positive and negative deviations, for all mobile phones and objects.

Figure 3 illustrates the front and back of the 3D model of the Testy, derived from the respective image data set. The deviations are highlighted in colour (green = 0.1 mm). All three-dimensional models demonstrate a pattern of systematic deviations, with the highest levels of discrepancy observed in the challenging-to-record apertures of the Testy. These deviations are evident in both orange and blue parts, with the red areas exhibiting the most pronounced discrepancies. The image data set from the iPhone 15 Pro Max (24 MP) yielded the most optimal visual results with minimal systematic deviations. Conversely, the photos from the Galaxy S21+ (64 MP) exhibited the least favourable visual outcomes.

The technical specifications of the image data processing of Testy using Polycam with iPhone 15 Pro Max is summarised in Table 5. Nevertheless, there are factors that indirectly affect the quality and, consequently, the resolution of the exported 3D model. The export settings can be adjusted in order to influence the quality of the exported 3D model. When a 3D model is exported, the user has the option to adjust the quality and file size, which in turn affects the texture resolution and level of detail. In the case of cloud processing, different quality levels are often available (e.g. standard, medium, high, RAW). These quality parameters also determine the level of detail of the model.

Object	Testy
Sensor	iPhone 15 Pro Max
Image resolution used	24 / 48 Mpix
# photos	231 / 220
Polycam file size	8 / 7.1 MB
Polycam quality	RAW (highest quality)
# triangles (cleaned)	64.586 / 50.866
OBJ file size (cleaned)	7.7 / 6.0 MB
Ø deviation [mm] (Geomagic)	+0.27 -0.29 / +0.31 -0.13
Std. dev. [mm] (Geomagic)	0.25 / 0.27
Ø span [mm] (Geomagic)	0.56 / 0.44

Table 5. Technical specifications of the image data processing of Testy using Polycam (smartphone App).

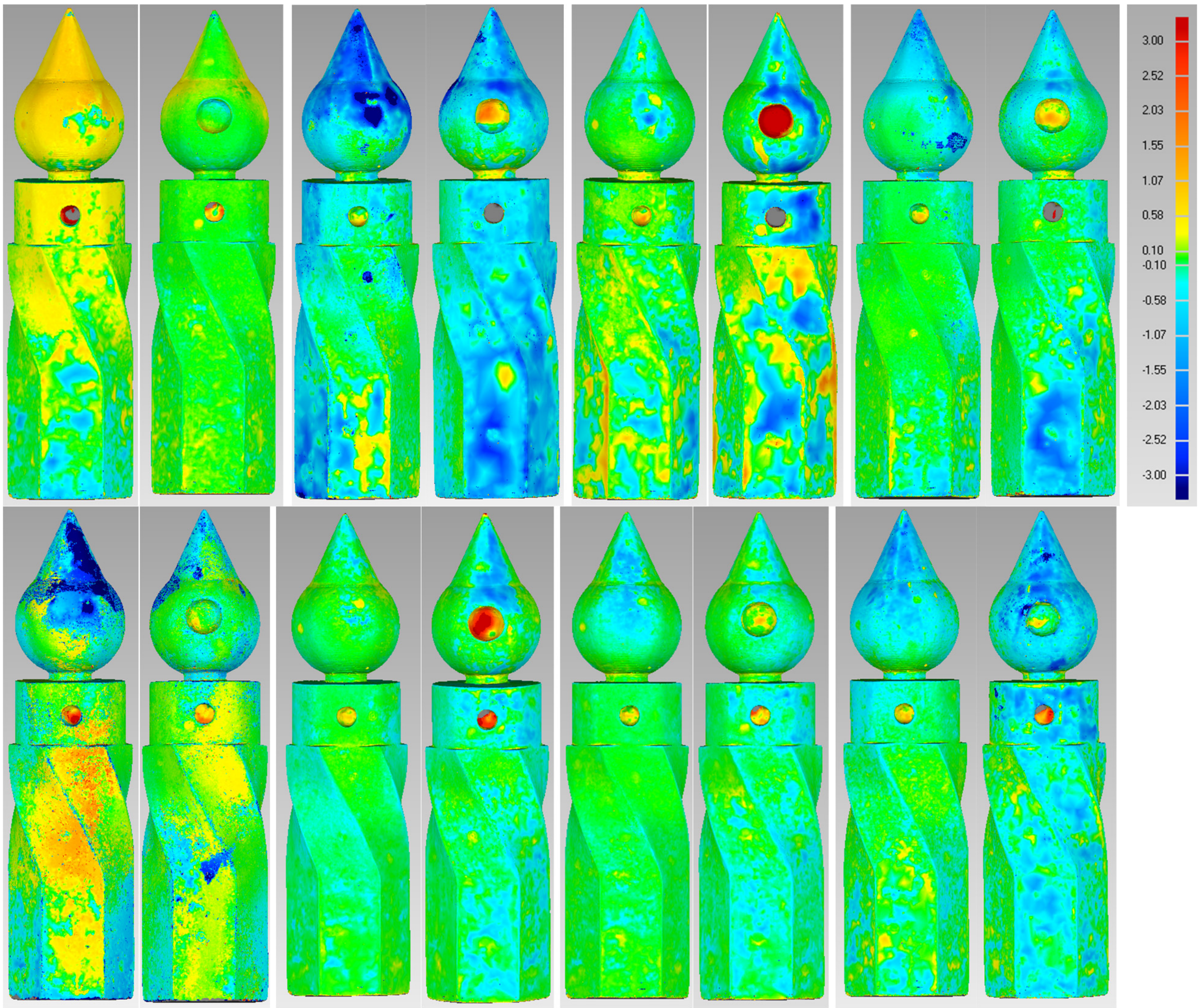

Figure 3. 3D models of Testy with coloured 3D deviations (green = 0.1 mm) using Geomagic Wrap in the sequence as in Table 4. Top row (front and back): Nikon D7500, Galaxy S21+ (64 MP), Galaxy S22, Galaxy S23, bottom row: Galaxy S24 Ultra, iPhone 13 Pro (12 MP), iPhone 15 Pro Max (24 MP), iPhone 15 Pro Max (48 MP)

Subsequently, the exported 3D model was scaled in Geomagic Wrap by measuring the distances within the model to ascertain the scale after the surrounding area has been deleted. Very similar results of the 3D comparisons between the models generated with Polycam and the reference data are shown in Figure 4.

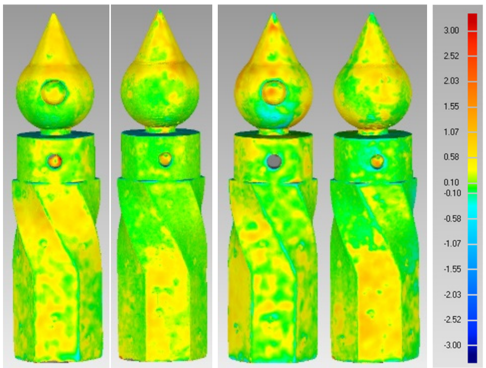

Figure 4. Coloured deviation plot of the Testy in relation to the reference generated using Polycam with iPhone 15 Pro Max (24 MP left and 48 MP right).

Figure 5 illustrates the front and back of the 3D model of the Moai figure, derived from the respective image data set. The deviations are highlighted in colour (green = 0.1 mm). Once more, the image data set from the iPhone 15 Pro Max (here 48 MP) yielded the most accurate visual and geometrical result, exhibiting no systematic deviations. In contrast, the images captured by the Samsung Galaxy S24 Ultra camera exhibit the poorest geometric and visual quality, with systematic deviations (in blue), despite the high resolution of 200 megapixels and the high number of triangles.

Figure 6 illustrates the front and back of the 3D model of the Einstein bust, derived from the respective image data set. The deviations are highlighted in colour (green = 0.1 mm). The average deviations from the reference data were less than 1 mm for all 3D models created. The iPhone 13 yielded the most accurate results with the least variability, whereas the Samsung S24 Ultra camera exhibited the least favourable outcomes (Table 4), characterised by a considerable number of triangles with systematic deviations (see the blue areas in Figure 6) from the

https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-211-2024

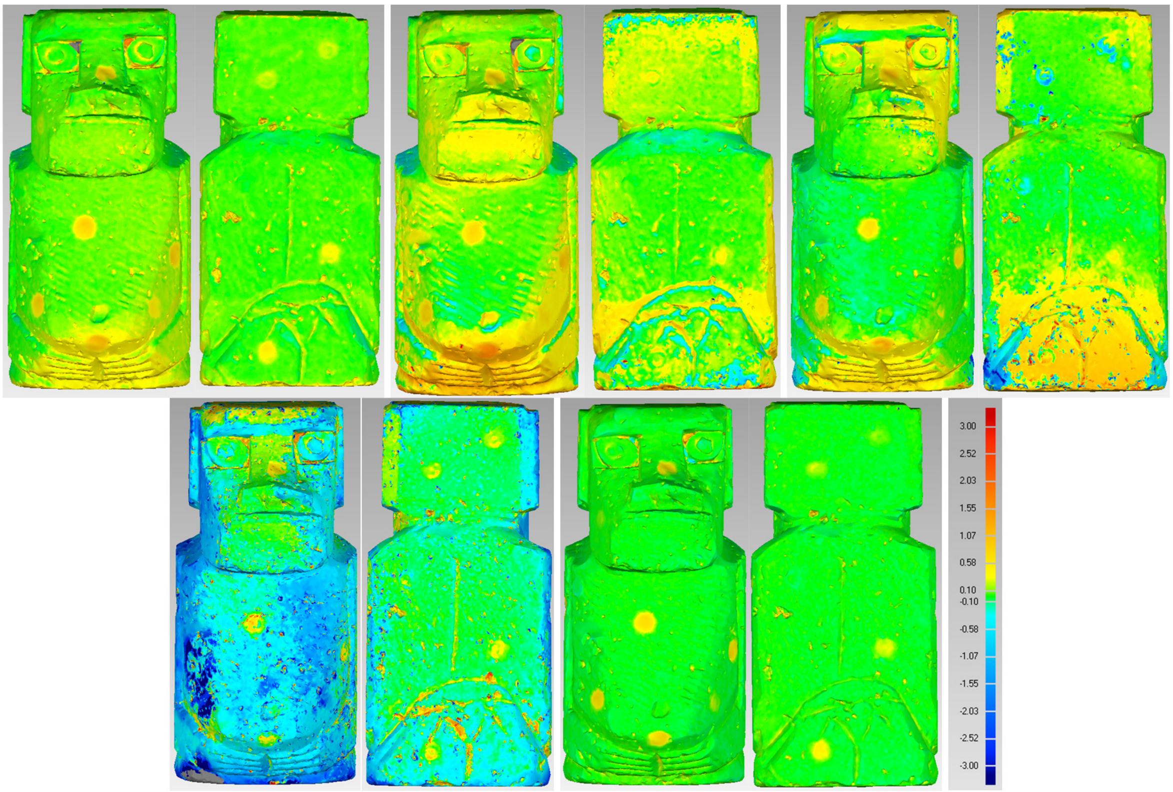

Figure 5. 3D models of the Moai figure with coloured 3D deviations using Geomagic Wrap in the sequence as in Table 4. Top row: Nikon D7500, Galaxy S22, Galaxy S23, bottom row: Galaxy S24 Ultra, iPhone 15 Pro Max (48 MP).

reference. Nevertheless, the discrepancies between the individual three-dimensional models of the Einstein bust are insignificant.

An adjusted plane was calculated in the point clouds of the granite slab, where the edge areas were removed, in order to determine the deviations from this plane in accordance with

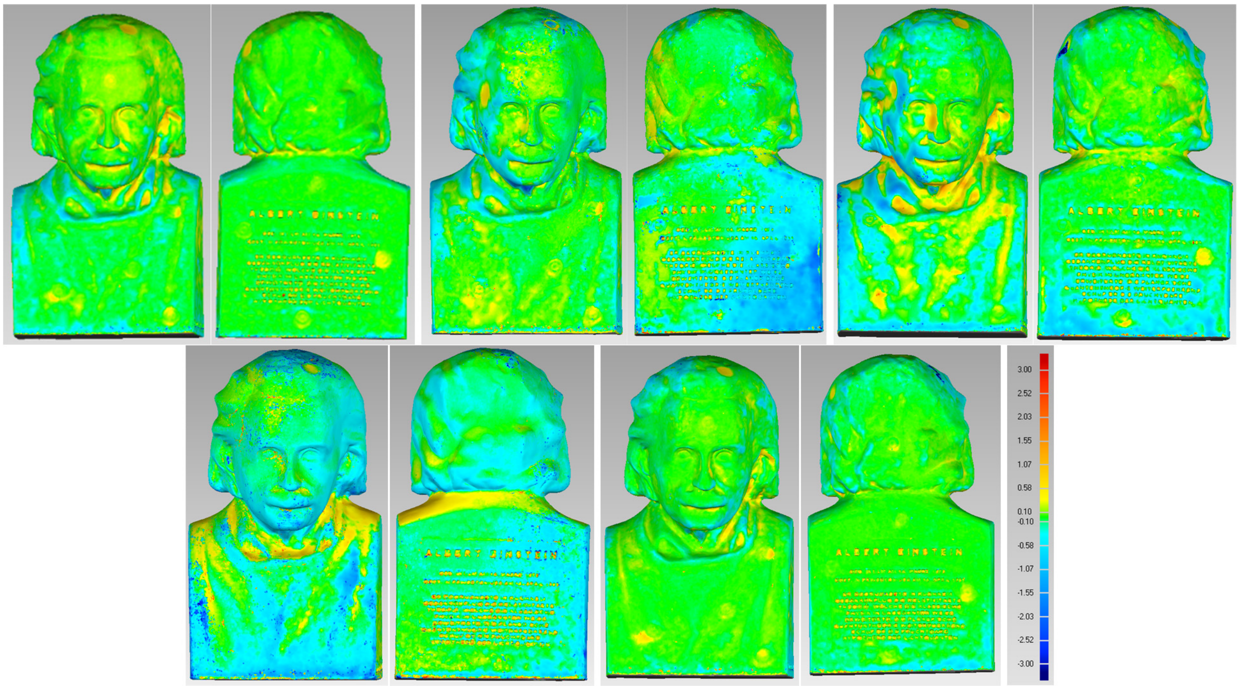

Figure 6. 3D models of Einstein bust and coloured 3D deviation analyses using Geomagic Wrap in the sequence as in Table 4. Top row: Nikon D7500, Galaxy S21+ (64 MP), Galaxy S22, bottom row: Galaxy S24 Ultra, iPhone 13 Pro (12 MP).

https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-211-2024

VDI/VDE Guideline 2634 (Sheet 2) as the *flatness measurement error RE* (VDI/VDE 2634, 2002). The flatness measurement error RE is defined as the range of the signed distances of the measuring points from the levelling plane, which is calculated using the least squares method. The guideline VDI/VDE 2634 (Sheet 2) 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 2634, 2002). 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 granite slab to determine the quality parameter flatness measurement error RE. The results of the investigations are also presented in Table 4 showing only very small deviations in relation to the adjusted plane except the Samsung Galaxy S22 and S23 (Figure 7).

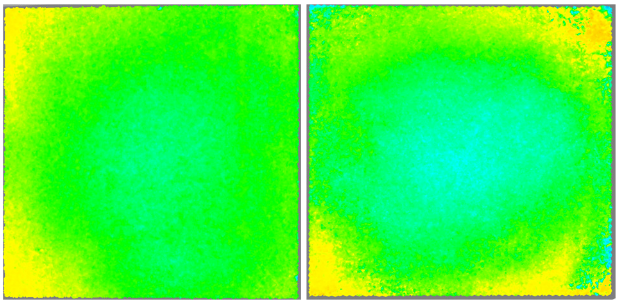

Figure 7. Coloured deviation plot of the granite slab in relation to the adjusted plane generated from the photos of Galaxy S22 (left) and S23 (right).

7. Conclusion and Outlook

In this study, a series of mobile phones (Android and iOS) were subjected to laboratory analysis for the purpose of recording small objects (up to 40 cm in height) with regard to geometric accuracy. A comparison with high-precision reference data from a structured-light projection system (ATOS 5) demonstrated that 3D models of the captured objects could be achieved with a sub-millimetre deviation using the photos from smartphones. However, systematic effects in the deviations from the reference data were occasionally observed in the generated models, although these were not significant due to the small deviations. The camera of the Samsung Galaxy S24 Ultra typically produces the least accurate results for 3D models, exhibiting systematic deviations in some instances despite its high resolution of 200 megapixels. In contrast, the iPhones demonstrated comparatively superior performance.

A more detailed examination of the meshing of the various recording systems reveals a notable similarity to the technical design of the image sensors. It is evident that the number of meshes or triangles in the Galaxy S24 Ultra image data is considerably higher than that of the other images. Concurrently, the calculated discrepancies from the reference objects are the most significant. One potential explanation is the parameter designated as 'pixel size'. Both the Galaxy S24 Ultra and the iPhone 15 Pro Max have a sensor with a format of 1/1.3 inches (based on a 4:3 image ratio, this corresponds to a sensor size of 9.2×7.6 mm). However, the maximum resolution of 200 MB of the S24 Ultra results in a pixel format of approximately 0.56 x 0.62 µm, whereas a single pixel of the iPhone's 48 MB image is 1.22×1.22 µm. It can be surmised that the iPhone has superior light sensitivity and reduced image noise due to its larger pixel format. This is evident in the comparative analysis of the calculated quality characteristics of both smartphones. Furthermore, the exceptional performance of the Nikon D7500 (pixel size 4.2 µm) lends support to this hypothesis.

The results of the 3D models obtained with the SLR camera are still slightly superior to those obtained with the mobile phones, although the difference is not significant. The advantages of the SLR camera are the interchangeable lenses, which allow for flexible use, and the ability to adjust the aperture, which enables the photographer to achieve a good depth of field. In comparison to the geometric accuracy analyses of the hand-held 3D scanners with the same reference objects, the smartphones demonstrated results that were similarly accurate (Kersten et al., 2016b; Kersten et al., 2018). Some handheld 3D scanners exhibited evident scale errors, indicating that the scanners were not calibrated with sufficient stability. Only the expensive 3D scanners that could be calibrated before the measurement achieved significantly superior results.

In addition to the 'Polycam' app (Polycam, 2024), which was used in this study, a plethora of analogous systems can be found in app stores that are designed for users with a specific interest. It is evident that less significance is attributed to prior technical (geodetic-photogrammetric) training, in accordance with the principle that "if you can take photos, you can also model 3D", which can be regarded as a conventional "black box" concept. Consequently, the parameterization of the calculation processes is considerably constrained, with only a few selection options available. A case in point is the lack of information regarding the image resolution of smartphone cameras utilized in the calculation process.

It is anticipated that in the future, the functionality of smartphones will continue to evolve in a manner that will increasingly align them with that of SLR cameras. This will result in the quality for the creation of 3D models with numerous software programmes and corresponding apps meeting the geometric requirements of many applications. Consequently, smartphones are becoming an increasingly prevalent photogrammetric measuring system and are already an attractive alternative to conventional measuring systems.

Acknowledgements

The authors would like to express their gratitude to Ingo Jahn and Claudia Rajczak of GDV Systems + Solutions GmbH in Bad Schwartau, Germany, for undertaking the scanning of the reference bodies using the ATOS 5 structured light system.

References

Bakuła, K., Flasiński, A., 2013. Capabilities of a smartphone for georeferenced 3dmodel creation: An evaluation. *Conference Proceedings of 13th International Multidisciplinary Scientific Geoconference SGEM 2013*, Albena, Bulgaria, 85-92.

Carl Zeiss GOM Metrology, 2024. ZEISS ATOS 5 Brochure EN. https://www.zeiss.com/metrology/en/systems/optical-3d/3d-scanning/atos/atos-5.html, last access October 23rd, 2024.

Elias, M., Eltner, A., Liebold, F., Maas, H. G., 2020. Assessing the influence of temperature changes on the geometric stability of smartphone-and raspberry pi cameras. *Sensors*, 20(3), 643. doi.org/10.3390/s20030643.

Elias, M., Kehl, C., Schneider, D., 2019. Photogrammetric water level determination using smartphone technology. *The Photogrammetric Record*, 34(166), 198-223. doi.org/10.1111/phor.12280.

Fagot, A., 2023. Apple iPhone 15 Pro Max: Jetzt ist auch bekannt, welche Kamera-Sensoren erneuert wurden und welche nicht. NotebookCheck, https://www.notebookcheck.com/Apple-iPhone-15-Pro-Max-Jetzt-ist-auch-bekannt-welche-Kamera-Sensoren-erneuert-wurden-und-welche-nicht.755133.0.html, last access November 7th, 2024.

Fang, K., An, P., Tang, H., Tu, J., Jia, S., Miao, M., Dong, A., 2021. Application of a multi-smartphone measurement system in slope model tests. *Engineering Geology*, 295, 106424.

Kersten, T., 2020. The Smartphone as a Professional Mapping Tool. https://www.gim-international.com/content/article/the-smartphone-as-a-professional-mapping-tool.

Kersten, T., Omelanowsky, D., Lindstaedt, M., 2016a. Investigations of Low-Cost Systems for 3D Reconstruction of Small Objects. *Lecture Notes in Computer Science (LNCS),* 10058, Springer Internat. Publishing Switzerland 2016, 521-532.

Kersten, T., Przybilla, H.-J., Lindstaedt, M., 2016b. Investigations of the Geometrical Accuracy of Handheld 3D Scanning Systems. *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 2016(5-6), 271-283. doi.org/10.1127/pfg/2016/0305.

Kersten, T., Starosta, D., Lindstaedt, M., 2018. Comparative Geometrical Accuracy Investigations of Hand-held 3D Scanning Systems - An Update. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-2, 487-494. doi.org/10.5194/isprs-archives-XLII-2-487-2018.

Kersten, T., Timm, F., Zobel, K., 2024. Development of a Photogrammetric 3D Measurement System for Small Objects using Raspberry Pi Cameras as low-cost Sensors. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVIII.

Luetzenburg, G., Kroon, A., Bjørk, A. A., 2021. Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences. *Scientific Reports*, 11(1), 1-9. doi.org/10.1038/s41598-021-01763-9.

Masiero, A., Fissore, F., Pirotti, F., Guarnieri, A., Vettore, A., 2016. Toward the use of smartphones for mobile mapping. *Geo-Spatial Information Science*, 19(3), 210-221.

Polycam, 2024. 3D scanning platform. https://poly.cam/, last access October 31st, 2024.

Quispe-Enriquez, O. C., Valero-Lanzuela, J. J., Lerma, J. L., 2023. Smartphone photogrammetric assessment for head measurements. *Sensors*, 23(21), 9008. doi.org/10.3390/s23219008.

Reulke, R., Misgaiski, M., 2012. Test body “Testy” for Laser Scanning and Optical Systems. *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 2012(6), zum Titelbild.

Saif, W., Alshibani, A., 2022. Smartphone-based photogrammetry assessment in comparison with a compact camera for construction management applications. *Applied Sciences*, 12(3), 1053. doi.org/10.3390/app12031053.

Tanskanen, P., Kolev, K., Meier, L., Camposeco, F., Saurer, O., Pollefeys, M. (2013). Live metric 3D reconstruction on mobile phones. *Proceedings of the IEEE International Conference on Computer Vision*, 65-72.

VDI/VDE 2634, 2002. Optical 3-D Measuring Systems – Optical Systems based on Area Scanning. VDI/VDE Guideline 2634, Part 2, Beuth Verlag, Berlin.

Yilmazturk, F., Gurbak, A. E., 2019. Geometric evaluation of mobile-phone camera images for 3D information. *International Journal of Optics*, 2019(1), 8561380.

Zhang, C., Lindner, S., Antolovic, I. M., Mata Pavia, J., Wolf, M., Charbon, E., 2019. A 30-frames/s, 252×144 SPAD Flash LiDAR with 1728 Dual-Clock 48.8-ps TDCs, and Pixel-Wise Integrated Histogramming. *IEEE Journal of Solid-State Circuits*, 54 (4), 1137-1151. doi.org/10.1109/JSSC.2018.2883720.