Investigations of Low-Cost Systems for 3D Reconstruction of Small Objects

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Abstract. In this paper geometric investigations are presented, which demonstrate the potential of the low-cost recording systems DAVID SLS-1 and Microsoft® Kinect for sustainable use in applications for architecture, cultural heritage and archaeology. From the data recorded with DAVID SLS-1 and Microsoft® Kinect 3D models were produced by different programs and these were examined in relation to handling, quality and reliability in further post processing. For the investigations a number of 3D objects with different surface forms, including a test body, were scanned using the structured light system ATOS I 2M from GOM as references. To compare the results of the Kinect and the SLS-1, digital surface models of this test body were automatically generated using image-based low-cost recording systems (Nikon D7000). As a result of these 3D comparisons to the ATOS reference data a standard deviation of 1.5 and/or 1.6 mm was obtained with the structured light system SLS-1 and/or with the Kinect, while with the image-based 3D reconstruction methods of VisualSFM/CMVS a higher standard deviation of up to 0.2 mm was achieved. Although the introduced low-cost structured light system David SLS-1 could not show the geometrical accuracy of a high end system (ATOS I) of approx. 0.04 mm, it is useful for the 3D recording of smaller objects (size up to 50 cm) with a reduced accuracy for several different applications.

Keywords: 3D, automation, comparison, image matching, modelling, point cloud, reconstruction

1 Introduction

For 3D shape recording of small and complex objects modern systems typically work according to the triangulation principle. For a long time these systems were only available at the expensive, high-end of the market, but in recent years affordable options have become increasingly available for users with smaller budgets. Current low-cost systems are available on the market but neither the quality nor the quantity of the recorded data is often considered in public discussion. However, contributions from Hieronymus et al. [1], Wujanz et al. [2], Khoshelham [3] and Boehm [4] present test results of 3D sensors from the low-cost field and the gamer market. Since the market for 3D consumer sensors is constantly growing, an examination of this equipment regarding reliability and accuracy for measuring tasks is an obvious requirement. Results of empirical accuracy tests are presented in [5], in which models from image-

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based low-cost 3D reconstruction methods are compared with reference data of higher accuracy.

The applications of so-called low-cost systems are to be found predominantly within the field of archaeology and cultural heritage, in which the structured light projection procedure is often used by preference. Thus, Sablatnig & Menard [6], Akca et al. [7], McPherron et al. [8], Bathow & Breuckmann [9] described that structured light scanners are widely adopted for these applications, since the contactless procedure is particularly well suited for the 3D documentation of small objects. First test results with Microsoft Kinect were presented by Wujanz et al. [2], Khoshelham [3] and Smisek et al. [10], while Mankoff & Russo [11] have also reported on experiences with the Kinect in glaciological, bathymetrical and geomorphological applications.

In the present contribution the potential of both low-cost systems DAVID SLS-1 and Microsoft® Kinect has been evaluated in comparison to image-based reconstruction procedures using several test objects as practical examples. Reference measurements of the different test objects were recorded with a structured light system (GOM ATOS I 2M).

2 Low-Cost Systems Evaluated

In these investigations a total of three low-cost recording systems was evaluated: (a) the Microsoft® Kinect [12], (b) the DAVID SLS-1 [13], which both work with an active (projector) and a passive (camera) sensor using the triangulation method, and (c) an image-based recording system (using different digital SLR cameras).

The Kinect was used in combination with the ReconstructMe software [14] which is freely-available for non-commercial applications. This sensor, which originates in the gaming market, offers a resolution of 640×480 pixels with a measuring distance of 0.8 to 3.5 meters. The Kinect costs approximately €100. The operational and functional principle is described in [15]. The SLS-1 is a low-cost structured light system from DAVID Vision Systems GmbH in Koblenz, which commercially distributed this product including the software DAVID Laserscanner as a complete 3D recording solution at a price of approximately €1700 (Nov. 2012). The integrated camera consists of a monochrome CMOS image sensor with a fixed focal length of 12mm and an image resolution of 744×480 pixels. The projector used in this system, which projects the structured light, is a commercial Acer K11. The base distance between camera and projector can be determined by system calibration in the software DAVID Laserscanner. Although the camera is monochrome, it is possible to texture the 3D models with colour by projecting several colours onto the object with the projector and by measuring the respective reflections from the object surface with the monochrome camera. DAVID software offers the whole workflow from object recording through scan registration to the export of the model, while with ReconstructME only recording and data export are possible. In principle, the measuring volume is unlimited for the MS Kinect, if certain conditions are considered as described in [14]. With the DAVID SLS-1 the maximum expanse of the object surface is 30-500mm. For image-based reconstruction procedures the digital SLR camera Nikon D7000 (4,938×3,264 pixels) was used, which can be very flexibly used for object recording. The following automatic generation of 3D point clouds and/or 3D object models was carried out with the open-source software Bundler [16] and PMVS2 [17], with the free available non-commercial software VisualSFM [18] as well as with the Autodesk Web service 123D Catch [19]. These three image-based 3D reconstruction methods are already briefly introduced in [5].

The evaluated recording systems are represented in Fig. 1; for detailed technical specifications the relevant manufacturers' web pages are referenced.

Fig. 1. Evaluated low-cost systems (f.l.t.r.): Nikon D7000, DAVID SLS-1 and MS Kinect

3 Evaluation Criteria and Methods

3.1 System Stability

The measuring systems DAVID SLS-1 and MS Kinect can be calibrated and prepared for data recording (the digitization procedure) within a few minutes by an experienced user. In order to be able to meet a statement about the stability of the SLS-1, as the first investigation camera calibration was conducted twenty times every ten minutes. The interior (intrinsic) and exterior (extrinsic) parameters of the camera are summarized in the calibration report. The SLS-1 uses a camera model of Tsai [20].which includes the following interior orientation parameters: focal length f, radial distortion coefficient κ1, scale factor sx and the coordinates of the principle point cx and cy.

Fig. 2 illustrates the SLS-1 calibration setup (left) and the computed focal length C in pixels (px) for the observation period of 200 minutes, in which 20 calibrations were carried out with the software DAVID Laserscanner (version 3.4.0).

For system calibration the camera acquires images of an orthogonally constructed calibration field provided with targets (Fig. 2 left) and whose geometry is known. The lowest and highest value of the calibrated focal length in the calibration series has a wide margin of 3.5 pixels, whereby the largest deviation was registered in minute 150. Unlike the other values, the series of measurements in minutes 30 - 60, 90, 110, 160 and 200 match each other well since their deviations are only approx. one pixel. In principle all values are evenly distributed, but a descending trend is clearly observable. Additionally, observation of the remaining intrinsic parameters (parameters of interior orientation) took place during these tests. It was observed that the location of the principle point in x-direction varies by only approximately 2.5 pixels. On the other hand, a span of 4 pixels is shown in the y-direction and it rises continuously starting from the first measurement. The scale factor varies around the value 0.084; it has the largest deviation of 0.0001 from the average value in minute 70. Although the temperature environment in the laboratory was constant, the computed parameters of interior orientation appeared to vary arbitrarily. This demonstrates a minor instability of the SLS-1, which also might affect the geometrical results of data recording.

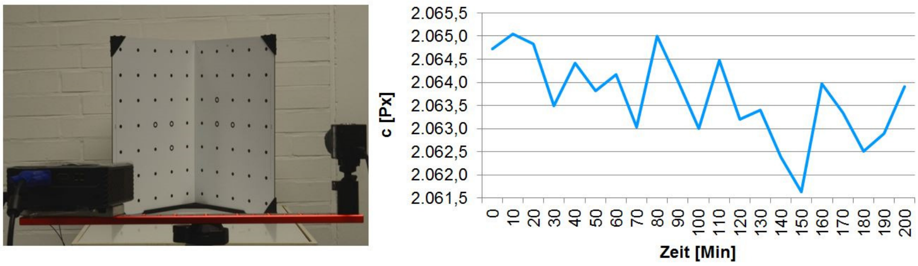

Fig. 2. DAVID SLS-1 (software version 3.4.0) – Calibration setup (left) and the variation of the focal length (right) over the time period of 200 minutes

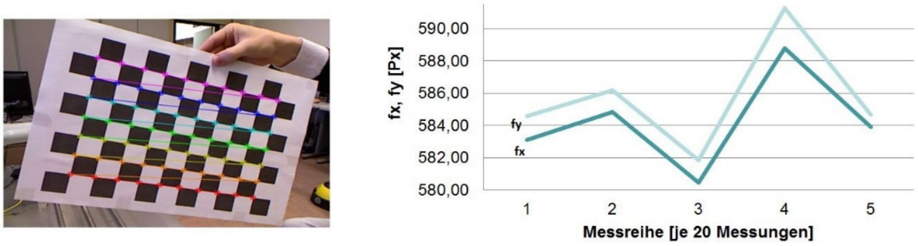

Fig. 3. MS Kinect – calibration pattern (left) and the variation of the focal length (right)

In order to evaluate the stability of the Kinect on the basis of system calibration results, 20 photographs were manually taken from different positions and were stored in a log file (protocol of results). This procedure was repeated in a series of five measurements. The intrinsic parameters of the Kinect include the camera constant in x and y-direction (fx/fy) and the coordinates of the principle point (px/py). The results of the series of measurements are illustrated in Fig. 3, which cannot be compared with the series of measurements in Fig. 2.

The span of the focal length is up to 10 pixels (see measurement series 3 and 4 in Fig. 3) for all series of measurements, whereby the largest deviation is approximately 3.5 pixels between fx and fy. On the other hand the values of the measurement series 1, 2 and 5 vary only approximately 1 pixel. Exactly the same results were achieved for the coordinates of the principle point. The largest deviation compared to the average value is registered in measurement 4 at approx. 4 pixels. Due to the fact that the values of interior orientation vary substantially despite calibrations under constant laboratory conditions, high system stability can also not be certified for the Kinect.

Investigations with DAVID SLS-1 and MS Kinect have demonstrated that the calibration results seem very arbitrary and are often inexplicable. However, the following measurements and 3D comparisons to reference data show that the differences for small objects are in the sub-millimetre range. Both the camera and the projector of the DAVID system were calibrated. The workflow and the results of the projector calibration are described in detail in [21].

3.2 Repeatability (Precision)

Repeatability (precision) is a criterion relating to the quality of a measuring procedure. It is also called as internal accuracy of a measurement, and is determined by the repetition of measurements. Using a gypsum figure, whose body size corresponds to the usual recording volume (91mm×156mm×91mm) of the system, the repeatability of the DAVID Systems was analysed.

In addition, the data capture of the gypsum figure was performed every six minutes during a time period of two hours. These six minutes correspond to the recording time of a real scanning object. In this way 19 different models were computed for analysis in Geomagic, each consisting of approximately 104,000 triangle points. A precision of 0.007mm resulted from the mean of the average deviations of the 19 difference models. The largest deviations to the master scan (first scan of the SLS-1 is set as reference) of +0.032/-0.041mm occur after half of the recording time and/or measurement series. In order to guarantee that the master scan meets the precision needs of the SLS-1 (0.2% of the measuring volume according to the manufacturer specifications), a 3D comparison to the reference model of the ATOS I was generated.

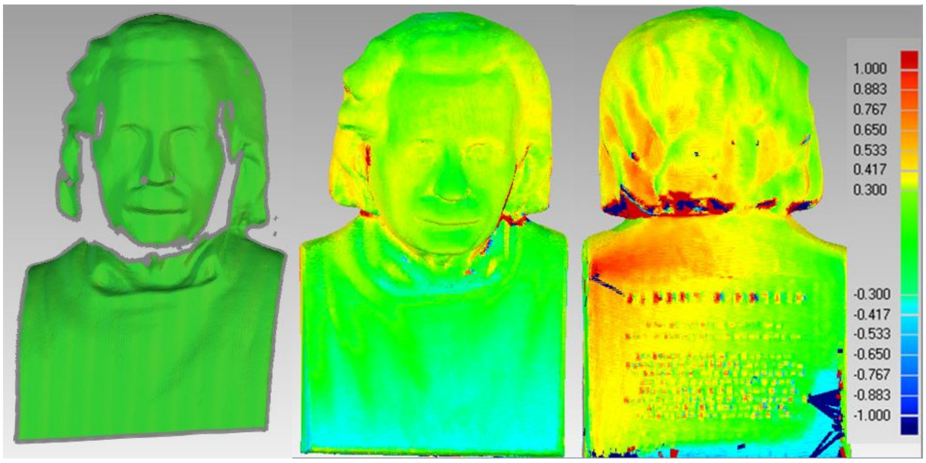

Fig. 4. Deviation between master scan (SLS-1) and scan 10 (left) as well as 3D comparison (centre and right) of both models (green = better than 0.3mm)

In Fig. 4 one can see that the average deviations of 0.23mm meet the precision needs of the SLS-1. The maximum deviation of 1mm at the edge results from measuring noise or light reflection. This can be ignored for the data analysis, since boundary regions can be smoothed and shrunken by edge operators within DAVID Software to ensure that they do not distract from the finished 3D model. In Fig. 4 (right) the 3D comparison makes it obvious that the generated model shows patch errors (registration of the scans) on the back of the gypsum figure with particularly bad results in the shoulder region where the deviations are up to a millimetre.

3.3 Analysis of Deviation by Comparison with Reference

In order to give a statement about the geometrical quality of the three systems used, the test body ”Testy”, which was introduced by Reulke & Misgaiski [22], from the Institute for Computer Science of the Humboldt university in Berlin was used (Fig. 5). First, as a reference, the test body was recorded in 52 scans with the ATOS I (17mm lens) (approx. 225,000 points). In particular, the surfaces of the model in the indentation and in the twist were difficult to scan.

Fig. 5. Test body Testy from the Humboldt university in Berlin (left and right) and the reference scan using ATOS I 2M (centre)

Subsequently, the test body was measured with the SLS-1 by twelve scans, which were registered to each other using the David software. During measurement the same problems occurred as with the ATOS I due to the occlusion of certain model areas. The scanning was carried out in approx. 15 minutes, while the production of a 3D model which followed took 105 minutes. For the recording with the system Kinect/ReconstructMe, seven attempts on a high performance computer (Intel Xeon CPU E5540 with 2.53 GHz, 12 GB RAM, NVIDIA GeForce GTX 690) were necessary in order to reconstruct the test body in real time. The automatic registration of the scans often failed during recording meaning that the recording procedure had to be aborted. However, with an error free recording process the 3D model of Testy was generated within three minutes. Co-registration as a post-processing step is not possible since the two data records cannot be registered on-line. The acquisition of 54 photos with the Nikon D7000 (18mm lens) for the image-based 3D reconstruction procedure with Bundler/PMVS2, VisualSFM and 123D Catch was conducted within 15 minutes. For scaling of the object, two points on the test body were measured with a total station Leica TCRP 1201+. The distance between the two object points was determined with a standard deviation of 0.2mm. For the subsequent scaling of the different models Geomagic Qualify was applied using the computed distance between the two points. The speed of the subsequent 3D reconstruction of Testy depended upon soft- and hardware. A standard computer (Intel core 2 duo CPU T7700 with 2,40 GHz, 12 GB RAM and a NVIDIA GeForce 8600M GT) needed approx. 60 minutes with VisualSFM for generation of the 3D point cloud, while with Bundler/PMVS2 a point cloud was produced after 480 minutes. On the other hand after the photos were uploaded on the server the Autodesk web service 123D Catch needed approx. 10 minutes to make the computed 3D model available for download. In order to support the measuring algorithms for image orientation by providing appropriate textures in the object background, the photographs were taken after putting the test body on a newspaper (Fig. 5). In post processing triangle meshes were computed in Geomagic using the point clouds from Bundler/PMVS2 and VisualSFM. Finally, all meshed models of Testy were compared with the reference data from ATOS I in Geomagic Qualify. Firstly a rough registration of the five models to the reference model was manually undertaken using identical points. This was later refined using the ICP algorithm with the best fit method. The results of 3D comparisons between the reference model from the high-end system ATOS I, the two evaluated low-cost systems and the image-based reconstruction procedures are represented in Fig. 6.

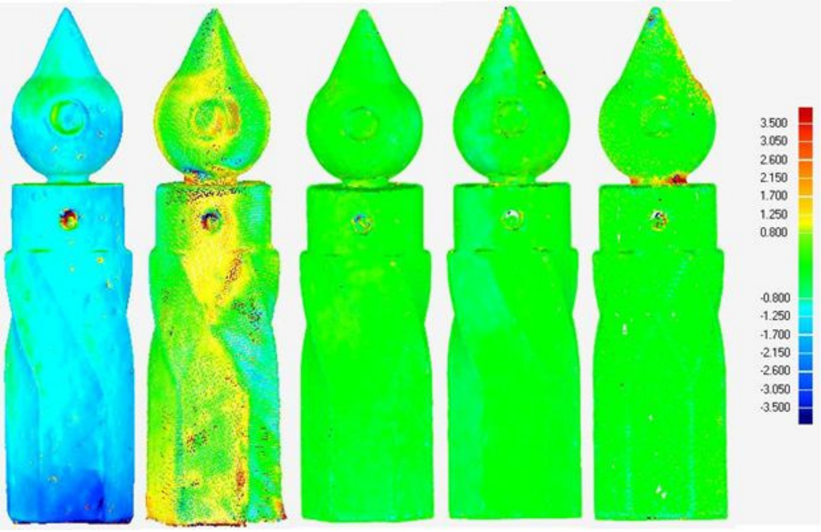

Fig. 6. Generated 3D models of Testy in comparison to ATOS I 2M (f.l.t.r.): DAVID SLS-1, MS Kinect, VisualSFM/CMVS, Bundler/PMVS2 and Autodesk 123D Catch (green < 0.8mm)

In the results of 3D comparison between SLS-1 and the reference systematic effects (negative deviations) are clearly consistently distributed over the entire body (see Fig. 6 left). It is to be assumed that these systematic deviations are caused by a scaling error in the SLS-1 data. In contrast the deviations between the Kinect model and the reference are unevenly distributed, since the data capture with ReconstructMe was also carried out very unevenly (recording start and stop). However, the models from image-based 3D reconstruction procedures show only very small deviations.

In Table 1 the results of the 3D comparison, which were generated in Geomagic, are summarised. They show that the image-based reconstruction procedures achieved significantly better results for maximum and average deviation as well as for standard deviation as the two tested systems SLS-1 and MS Kinect. Similar good results for image-based reconstruction procedures were shown by Kersten & Lindstaedt [23] for small to medium sized objects in archaeology and cultural heritage.

Table 1. Deviations to reference for the models of the test body Testy generated by different systems [mm].

System / Software	# triangles	Max. dev.	Av. dev. +	Av. dev. -	Std. dev.
DAVID SLS-1	1.650.404	21.5	2.3	1.5	1.5
Kinect/ReconstMe	389.628	15.3	0.9	0.9	1.6
VisualSFM	464.246	2.7	0.1	0.1	0.2
Bundler/PMVS2	405.980	4.0	0.1	0.1	0.3
123D Catch	14.034	5.2	0.5	0.3	0.7

Additionally, three more objects were used for a 3D comparison of the results from the DAVID SLS-1 and the data from the ATOS I 2M (reference). The three objects were composed of different materials: cast iron for the wheel hub, bronze for the penguin, and gypsum for the Einstein bust. These objects were scanned as follows: wheel hub – 70 scans with ATOS, 24 scans with SLS-1, penguin – 70 scans with ATOS, 6 scans with SLS-1, and Einstein bust – 21 scans with ATOS, 17 scans with SLS-1. The results of the 3D comparison are illustrated in Fig. 7 and summarised in Table 2. The difference plots in Fig. 7 show that the problematic surface areas for scanning with the SLS-1 are the edges of the object. Nevertheless, some systematic effects (indicated in blue) are also illustrated in the difference plots.

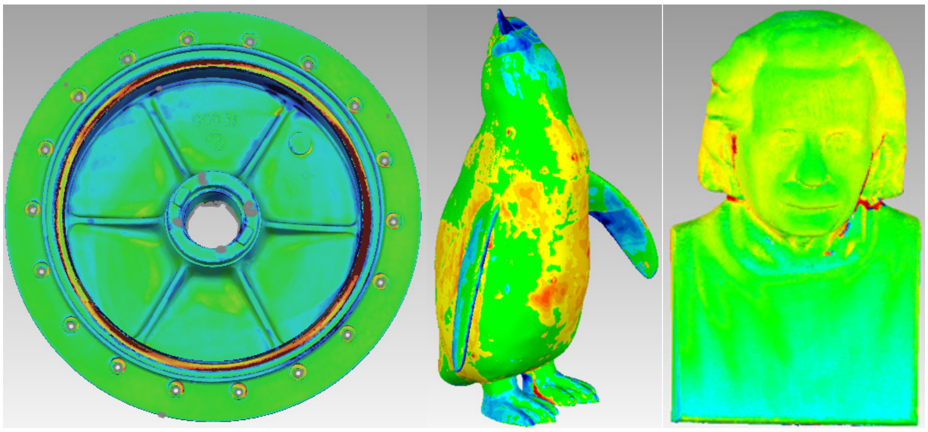

Fig. 7. Generated 3D models with DAVID SLS-1 in comparison to ATOS I 2M – wheel hub (left, green = ±0.5mm), penguin (centre, green = ±0.2mm) and Einstein bust (right, green = ±0.3mm) – to show systematic deviations

Table 2. Deviations to reference for the models of three test objects generated by DAVID SLS-1 [mm].

Test body	Size [cm^3]	# triangles	Max. dev.	Av. dev. +	Av. dev. -	Std. dev.
Wheel	23×12×23	4.057.057	11.1	0.5	-0.7	1.2
Penguin	22×46×28	2.229.541	16.5	0.2	-0.2	0.4
Einstein	11×16×10	912.320	-13.6	0.3	-0.4	0.6

3.4 Polygon Decimation

Usually the modelling of object surfaces as polygon networks creates large data volumes, which makes representation of such data on terminal devices with low performance (e.g. Smartphones with 600 MHz processor) or on the Internet problematic. For this reason polygon decimation of meshed 3D models is the solution for such a task to guarantee fast access to the data. Results on polygon decimation of meshed models from terrestrial laser scanning data were already published in [24]. These results showed that one can reduce the data set of 3D models up to 10% without having significant losses to geometrical or visual quality.

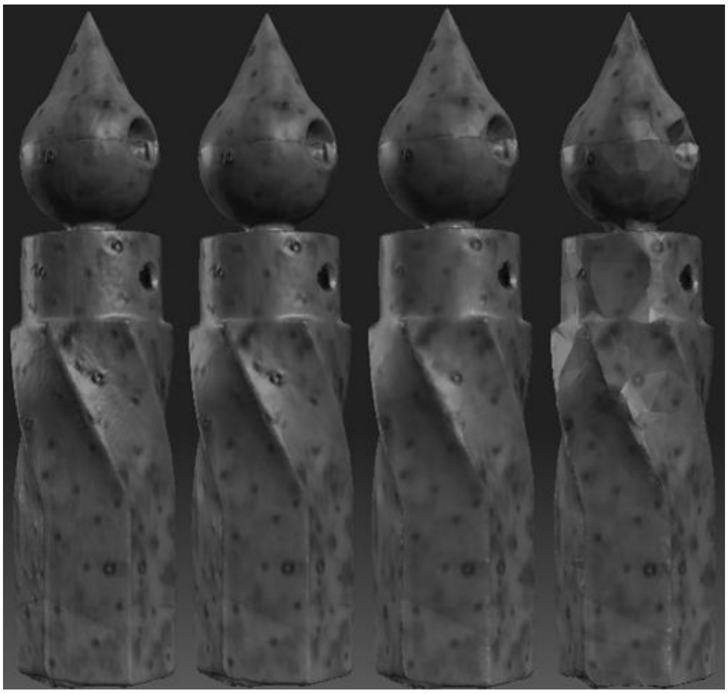

Fig. 8. Results of polygon decimation (f.l.t.r.): Testy 100%, 20%, 6% and 4%.

To verify this, the test body Testy was examined in relation to polygon decimation using the data from the DAVID SLS-1. A file size of approx. 120 MB (1.7 million triangles) corresponds to 100% of the original data recorded for Testy. The percentage of polygon decimation can be defined by the user in the DAVID Laserscanner software. Up to a polygon decimation of 20% (approx. 290,000 triangles) there is no significant geometrical deviation to the original. However, the visual comparison of the test body reduced to 20% already shows smoothing effects at edges and at the targets. Nevertheless, the meshed models can be reduced up to 20% of the volume of data without accuracy losses. The results of the polygon decimation are represented in Fig. 8 for four 3D models of the test body Testy (100%, 20%, 6% and 4%).

4 Conclusion and Outlook

In this paper geometrical investigations under laboratory conditions showed that the two low-cost systems DAVID SLS-1 and Microsoft Kinect generate significantly worse results compared to image-based reconstruction procedures using digital SLR cameras. The 3D models generated from image-based reconstruction procedures are characterized by a high degree of automation and by very good quality. However, the two evaluated low-cost systems offer the advantage of on-line control of completed recording of the object and/or of the object space during the digitization process. On the other hand image-based reconstruction procedures automatically compute 3D point clouds and/or 3D surface models without direct access by the user meaning that gross errors become visible only after the computation from the photos. Nevertheless, the quality of the SLS-1 results corresponds to the accuracy after system calibration specified by the manufacturer (0.2% of the measuring volume). Unfortunately, no information about the algorithms used in the DAVID Laserscanner software is available to the user (e.g. registration, triangle meshing, etc.). The complete package DAVID SLS-1 is suitable for users who would like to produce digital 3D models with limited accuracy of small objects for various applications and within a short time. A further decisive criterion for the purchase of a SLS-1 is the attractive price, which is 25 times less than for high-end products (e.g. ATOS I 2 M). The results of the system Microsoft Kinect/ReconstructMe were better than from the SLS-1; however there is still substantial optimization potential in hard- and software for both systems. Efficient and successful 3D object recording with the Kinect requires repetition and/or practical experience by the user. Thus, several approaches are often necessary in order to achieve a useful result. Furthermore, a good computer with high performance graphics processor is necessary when using Kinect/ReconstructMe in order to obtain results at all. Generally, this low-cost system offer an economically accessible product for many users for providing contactless 3D object recording for digitization of objects (including in the field of education).

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