DETERMINATION OF MEASUREMENT ACCURACY OF OPTICAL 3D SCANNERS

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DOI: 10.17973/MMSJ.2016_12_2016183

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Nowadays, the use of optical 3D digitisation in metrology becomes more frequent and desired. Unfortunately, there are still no binding standards for determining measurement uncertainty of these systems and manufacturers of 3D scanners often use their own standards to define accuracy of their device. This paper introduces a methodology to assess the accuracy of digitisation using 3D optical scanners. The paper deals with practical implementation of an acceptance test for ATOS contact-less 3D scanners (from design and manufacturing of own test etalon, through the determination of its nominal dimensions, up to digitisation and evaluation) and publishes the results of several experiments demonstrating the impact of various factors on measurement accuracy.

KEYWORDS

Optical measurement, optical 3D scanner, 3D digitization, accuracy, calibration, Acceptance test, Atos

1 INTRODUCTION

Currently, the measurement of dimensional and shape precision in industrial practice is performed by conventional methods such as a contact method using coordinate measuring machines (hereinafter only CMM). Even though these machines provide one of the most accurate results [Flack 2011], they cannot be used in some cases. An example may be measurement of surfaces with very complex shapes.

That is the reason why laser and optical measurement systems, so called 3D scanners, are used more and more often. These scanners digitise the part, and the inspection itself is performed on a virtual model obtained by means of the digitisation process (for example [Harding 2013, Zhang 2013]). Inspection using these systems offer several crucial advantages such as fast measurement of parts, even with complex shapes, high data density and, above all, independence of results on part's rigidity. Due to the overall description of a measured part, it also allows to perform complex and objective analysis. However, the accuracy of these measurement methods is not so apparent. Generally, there are no strictly determined specifications for measuring uncertainty of optical 3D scanners. Their accuracy is usually not clearly quantifiable and we have to carry out various comparison tests.

Figure 1. GOM calibration etalon for so called Acceptance Test

Manufacturers of 3D scanners create their own standards and verify the precision of their devices in special metrological laboratories using etalons of ideal shapes such as spherical systems – see calibration etalon for performance of so called Acceptance Test (Fig. 1) for optical scanners manufactured by GOM [GOM mbH 2014].

Currently, optical 3D scanners are often used as a universal measurement and inspection device. Therefore, the user must be sure that he uses an optical scanner working in a defined range of accuracy. In long-term perspective the only way to meet this requirement is to use comparable criteria and regular inspection of the device (scanner). The manufacturer recommends to perform the acceptance test approximately once a year or more often for specific industries. Naturally, it is necessary to keep these intervals in manufacturing companies regarding quality and certification standards. However, these inspections are often underestimated in research laboratories and are not performed within the recommended intervals, or at all. Performance of the test in an approved or manufacturer's laboratory is very costly, while the whole measurement system is not available for several days or week after it is sent to the manufacturer for inspection. However, the accuracy and reliability of the system in development laboratories is crucial as well. That is why we focused on research with the aim to determine accuracy of optical 3D scanner measurement in laboratory conditions. We were interested in the existence of possibility to design and manufacture a calibration etalon that would enable to reliably perform a test of measurement accuracy what would be comparable with the acceptance test. This would facilitate implementation of own inspection of system's reliability in shorter intervals and with significantly reduced costs. Additionally, the approved etalon would be used for further testing and experiments.

During an analysis of research papers dealing with a similar issue, it was found out that these researches are often addressing only partial analyses or unilaterally focused experiments. One of the first tests of this type has already been made in 2003 by [Keller 2003], who tried using contact-less measurements to determine planar dimensions of machine parts. The aim was to analyse the origin of each error of this measurement method and to find a possibility to reduce this error to minimum. Recently, [Dokoupil 2013] performed an experimental identification of ATOS Triple Scan optical system deviations related to application of matting chalk and titanium coating. The aim of the research described in this literature was merely to assess measurement uncertainty when applying chalk and titanium powder, as well as to determine layer thickness of matting powders. Another significant research discussing the influence of matting coatings on the precision of 3D optical measurement was published by [Palousek 2015]. His team performing the research found out that while the chalk coating may reach the average thickness up to 44 μm, using titanium-white-based anti-reflection coating reduces the thickness approximately tenfold – down to 5 μm, offering a highly positive effect on the accuracy of digitisation process. A more detailed comparison of several scanning systems and assessment of 3D scanner precision was published by [Barbero 2011]. In order to determine the measurement uncertainty, the team performed measurement of several calibration elements such as sphere, cylinder and gage block. An uncertainty of 25 μm was determined during the Atos system measurement process.

Another interesting analysis concerning the evaluation of accuracy 3D scanners and researches regarding the various types of calibration artefacts or directly of calibration of optical systems, can be also found for example, in publications [Acko 2012, Burchardt 2015, Campanelli 2016, Dury 2015, McCarthy 2011]. The first of these papers [Acko 2012] describes three different types of artefacts for calibration, namely tetrahedron artefacts for testing the basic measurement capability of optical 3D devices, freeform verification artefacts for testing the capability of measuring complex geometry, and a large gear artefact for task related calibration of different types of CMMs. Other paper [Dury 2015] describes a verification facility that has been developed with the aim of providing a 3D optical scanner verification service to global industry ensuring greater confidence in their measurement capability. The device allows to simulate typical usage conditions where temperature and lighting may vary. In addition, a range of test artefacts have been specifically developed to identify scanners' sensitivity to colour, resolution, roughness, and laser scanning articulating arm scan velocity. The paper [McCarthy] states that documented standards for the verification of fixed CMMs fitted with tactile probes are now widely available, whereas verification procedures and more specifically verification artefacts for optical-based systems are still in their infancy. The paper further describes a freeform verification artefact that has been developed, calibrated and used to support a measurement comparison between a fixed CMM and a number of optical systems (laser triangulation scanning, photogrammetry and fringe projection). The research concludes that the accuracy of the optical-based systems tested is not as good as tactile probing systems.

Fairly extensive own analysis of measurement accuracy of contact-less optical 3D scanners was performed in 2015 by [Mendricky 2015]. This analysis focused primarily on inspecting digitisation of objects with various shapes. Also, the capabilities of 3D scanners to capture detailed elements on the measured parts were examined. However, even in this study or any other research available, the research was not in compliance with the standards. There have not been used procedures defined in the so-called acceptance test, which is decisive for checking the accuracy of 3D optical measurement systems.

2 OPTICAL MEASUREMENT SYSTEM

In case of our research, the objective was to evaluate the measurement accuracy and therefore design a calibration etalon for **ATOS 3D optical scanner** (see Fig. 2). Atos is an optical measurement system, whose measurement process is based on principles of optical triangulation, photometry and Fringe Projection method [Gorthi 2010]. This system is used in various industrial branches such as construction, production, quality control, design, etc.

Figure 2. ATOS optical 3D scanner with MV250 measuring volume

The most important part of the system is the optical 3D scanner itself, consisting of a projector, two cameras and a control unit. By choosing appropriate lens, we define the size of a 3D area in which the measured object will be scanned – so called measuring volume. Setting the volume is not only affecting the size of the measured part, but also significantly influences the density of measured points and the actual scanning accuracy. When designing the etalon, we focused on three available measuring volumes listed in Tab. 1.

Measuring volume	*Resolution*	*Measurement distance*
55×44×30 (hereinafter 55, SO)	0.04 [mm]	300 [mm]
250×200×200 (hereinafter 250)	0.18 [mm]	730 [mm]
700×560×560 (hereinafter 700)	0.50 [mm]	1030 [mm]

Table 1. Overview of the ATOS system measuring volumes

3 ACCEPTANCE TEST

As indicated above, the acceptance test is performed to verify measurement accuracy of optical systems. Based on characteristic parameters, it verifies whether the measurement system meets the quality limit parameters or not. The measured deviations must not exceed the limit values given by the manufacturer, which are specific for various scanner types, measuring volumes and parameters. The ATOS device test is governed by manufacturer's (GOM) specifications and is in accordance with the VDI/VDE 2634 – part 3 [VDI/VDE 2634 2008] standard, related to optical 3D systems. The standard describes the practical part of the test, defines the calibration etalon, characteristic values, measurement conditions and the evaluation method. The manufacturer determines further specifics that must be maintained during the test [GOM mbH 2012, 2014]:

- The sensor and its parts are factory-adjusted. Check whether the settings comply with the specification before performing reverification measurement. In case the settings do not comply with the specifications, set up the sensor according to the respective User Manual Hardware.
- Calibrate the sensor. Maintain the warm-up time and the calibration limit values.
- Carry out the measurements with the quality setting set to *High* and the resolution set to full.
- Select the exposure time so that the measuring images are well exposed. Avoid overexposures.
- Polygonise single scans to a mesh using the *Standard* setting.
- For calculating the spheres, the software uses only measurement data above a defined plane. This plane is aligned parallel to the artefact base plate. Also, its plane intersects the sphere at 10° south latitude. The software determines the spheres using the least squares method. During the process, the software rejects 0.3% of the measured values as outliers. This value corresponds to a 3 sigma setting.
- The software determines the *Length measurement error* parameter using Method C (see VDI/VDE 2634 Part 3 for more information).
- The ambient temperature and the artefact temperature have to be identical.
- The measuring environment must be free of mechanical vibrations.
- The ambient light must not vary extensively during the measurement. Avoid extremely bright external light sources.

3.1 Acceptance Test parameters

The rules of evaluation are based directly on the mentioned standard. However, when performing the Acceptance Test, the conditions are not as strict and the manufacturers have the right to choose their own methods. The parameters measured during the Acceptance Test are:

- Probing error form (PF)
- Probing error size (PS)
- Sphere spacing error (SD)
- Length measurement error (E)

When evaluating the parameters, the measured errors are compared to MPE_{xx} (*maximum permissible error*) parameter. This limit is set exclusively by the manufacturer of the measurement device.

Probing error form (PF) (Fig.3 - left) shows shape deviations (sphericity). The highest and the lowest deviation from an ideal sphere is being identified (from all scanned points).

$$\text{PF (sigma)} = \sigma \tag{1}$$

$$\text{PF (range)} = |\max - \min| \tag{2}$$

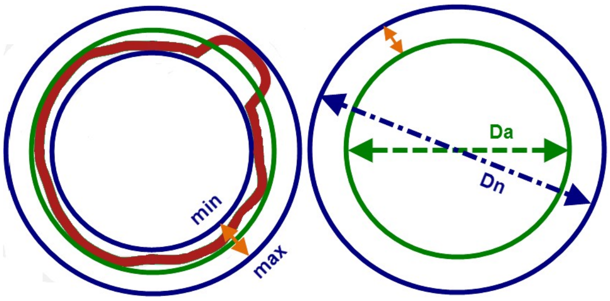


Figure 3. Schematic representation of the “Probing error” calculation [GOM mbH 2014]

Probing error size (PS) (Fig.3 - right) shows deviation of fitted sphere size. The sphere size is measured by means of *Fitting Sphere* method. The diameter error is described as a difference between D_a measured diameter and D_n reference diameter value.

$$\text{PS (size)} = D_a - D_n \tag{3}$$

Sphere spacing error (SD) (Fig. 4) shows spacing deviation of the two sphere’s centres. It is used to determine whether the scanner measures in the correct scale on a defined length.

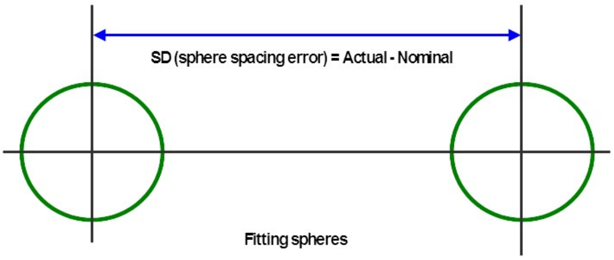


Figure 4. Schematic representation of the ”Sphere spacing error“ calculation [GOM mbH 2014]

Length measurement error (E) (Fig. 5) shows deviation of length measurement. It determines whether the scanner measures in the right scan, including the effect of the scan noise.

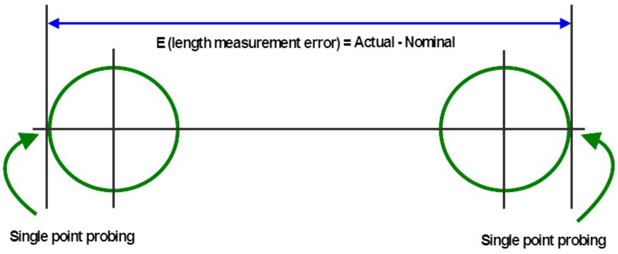


Figure 5. Schematic representation of the "Length measurement error" calculation [GOM mbH 2014]

4 CALIBRATION ETALON

In order to perform the test and evaluate the required parameters, it is necessary to use a proper calibration standard. The etalon must be designed so that it offers evaluation of more measuring volumes. Spherical objects are used in most calibrations (various metrology branches). The same applies when calibrating optical devices.

Due to usage of various lenses (measuring volumes) and regarding to evaluation parameters, the etalon consists of pairs of spheres with various diameters and spacings. In our case, 3 pairs of spheres were used. Their diameters and spacing were in accordance with the VDI/VDE 2634 standard and are listed in Tab. 2, and in Fig. 6.

Measuring volume	*Diameter of spheres*	*Sphere spacing*
55x44x30 (MV55)	8 [mm]	26 [mm]
250x200x200 (MV 250)	20 [mm]	115 [mm]
700x560x560 (MV 700)	40 [mm]	320 [mm]

Table 2. Selected dimensions of measured elements on the etalon

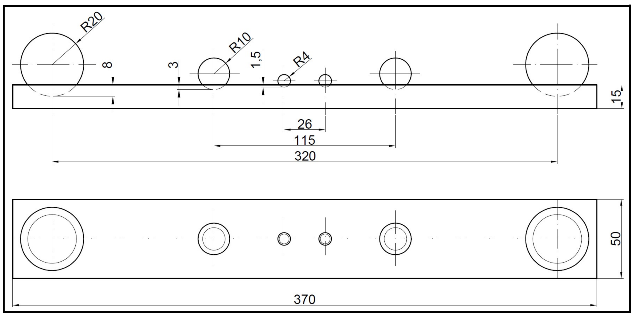


Figure 6. Etalon design for the Acceptance Test [Frkal 2015]

Stainless steel was selected as a base plate material, specifically AISI 304 chrome-nickel austenitic steel. The spheres were bought from Redhill Balls, a company with an office in Prague. Due to the requirement of having objects with small roughness, the balls are polished and made of AISI 304 material and offer G100 accuracy degree. Tab. 3 shows accuracy of balls provided by the manufacturer.

Grade	***Ball Diameter Variation***	***Deviation from Spherical Form***	***Surface Roughness***
G100	2.5 [µm]	2.5 [µm]	0.100 [µm]

Table 3. Degree of accuracy G100 according to ISO 3290 [Redhill 2016]

The balls were glued by means of two-component epoxy glue (Bison Epoxy Metal) into seatings in the base plate machined earlier. The created calibration etalon fitted with reference points is shown in Fig. 7.

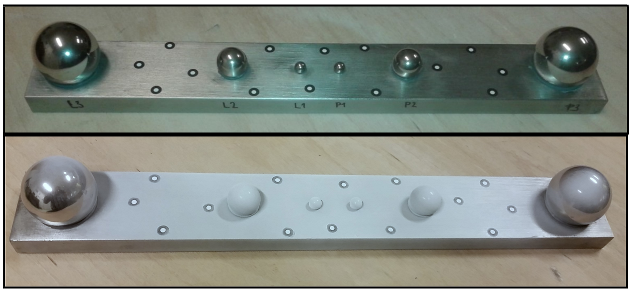


Figure 7. Physical model of the calibration etalon (with and without the matte coating)

4.1 *Determining nominal dimensions*

The real, for our purpose referential (nominal) element dimensions were repeatedly measured on DEA GLOBAL Status 7.10.5, a 3-axis coordinate measuring system, manufactured by Hexagon Metrology. The CMM measurement accuracy was higher by more than an order of magnitude in comparison to the assumed measurement accuracy of 3D scanners. The calibration sheet offers measurement accuracy of 2.5 µm. A thermal correction of dimensions to 20 °C was performed, while the measurement results were processed in a statistic manner (average values from ten measurements were calculated as well as type A, B and C standard measurement uncertainty). The results of variables along with U expanded uncertainty is shown in Tab. 4.

Measured variable	***Result of measurement***
Sphere L Ø8 mm	8.000 ± 0.005 [mm]
Sphere R Ø8 mm	7.999 ± 0.005 [mm]
Sphere L Ø20 mm	20.000 ± 0.005 [mm]
Sphere R Ø20 mm	20.000 ± 0.005 [mm]
Sphere L Ø40 mm	40.002 ± 0.005 [mm]
Sphere R Ø40 mm	40.001 ± 0.007 [mm]
Sphere spacing 26 mm	26.017 ± 0.005 [mm]
Sphere spacing 115 mm	115.005 ± 0.006 [mm]
Sphere spacing 320 mm	319.933 ± 0.007 [mm]
Outer distance 34 mm	34.016 ± 0.005 [mm]
Outer distance 135 mm	135.005 ± 0.006 [mm]
Outer distance 360 mm	359.935 ± 0.007 [mm]

Table 4. Measurement results of etalon on the CMM

4.2 *Scanning the etalon by means of ATOS II 400*

When performing an acceptance test, the procedure is precisely recommended by the aforementioned standard for scanning a calibration etalon. Scanning is performed in three series for each measuring volume. In each series, the position of the scanner towards the etalon is different, while in each position, a total of 10 images is created. During each measurement, the etalon must be stable and, of course, fitted with reference points. Since the spheres are very glossy, an anti-reflection coating in a form of titanium dioxide is applied. To obtain uniform thickness of anti-reflection coating is most commonly used aerograph (Airbrush) for application. In order to ensure high accuracy, all measurements were performed in constant conditions, specifically in temperature of 20 ± 1°C and relative humidity of 50 ± 10 %.

The measurement procedure is as follows [GOM mbH 2014] (1st measurement series):

- Place the etalon horizontally onto a rotary plate and ensure its stability.
- Tilt the scanner by 45° towards a vertical axis.
- Set the scanner distance so that the centre of measuring volume is located in the centre of axis linking the measured spheres.
- Create 8 images in each position. The etalon is rotated by 45° around its vertical central axis for each image.
- Set the scanner so that the centre of the measuring volume points to intersection of axes linking the spheres and the outer surface of the left sphere. In comparison to the initial position, rotate the etalon by 90° and create a ninth image.
- Rotate the etalon by 180°, and, similarly to the previous case, set the measuring volume centre to point at intersection of axes linking the spheres and the outer surface of the right sphere. Create a tenth image.

During the second, or third, measurement series, the procedure is analogical, but the scanner is tilted in its horizontal axis by 45° clockwise, or counter-clockwise. The imaging positions for 3rd measurement series are shown in Fig. 8.

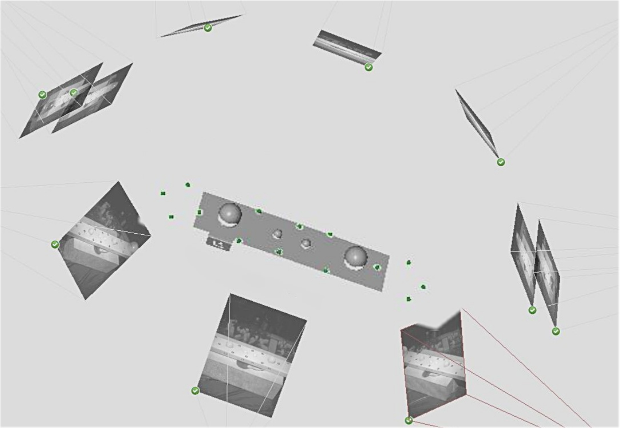
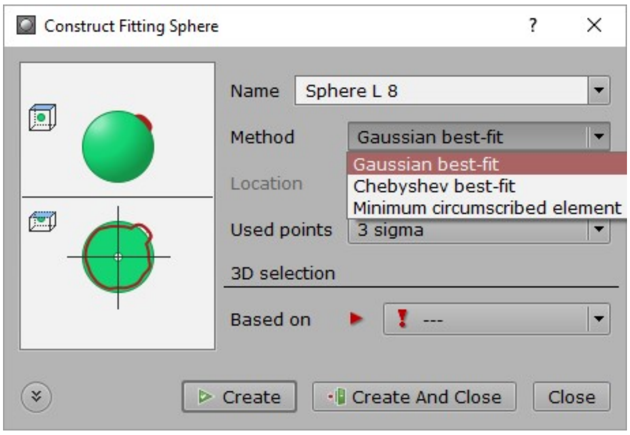


Figure 8. Position of individual images when scanning the etalon (MV 250, 3rd measurement series)

5 DATA EVALUATION

The next step was to process the scanned date in *GOM Inspect Professional* software v8, which provided information about the required values. In order to determine sphere diameters, a "Fitting Sphere" was used, allowing calculation of a geometrical element using a large number of scanned points (so called point cloud). In compliance with the standard, a "Gauss Best-Fit" was used as a calculation method, while 3σ (i. e. 99.73 %) points from the selection were used to calculate the element (see Fig. 9).



Name: Sphere L 8
Method: Gaussian best-fit
Gaussian best-fit
Chebyshev best-fit
Minimum circumscribed element
Used points: 3 sigma
Based on: ---

Figure 9. Construct Fitting Sphere feature

Calculation of sphere spacing was performed by creating a “2-point distance” inspection element, measuring distance between the centres of left and right spheres of the given pair.

5.1 *Parameters affecting the measurement accuracy*

There is a wide range of parameters that are affecting the accuracy of scanned data. Measurement conditions (such as ambient temperature, humidity, lighting, dust, etc.) can be influenced up to a certain point and adapted to the requirements. However, there are other variables that may vary during individual measurements, which are significantly affecting the measurement results, as confirmed by experiments. Among these factors are for example fitting the etalon with an appropriate anti-reflection coating (uniform layer), time since last calibration of the device, or a data evaluation method (software).

Effect of device calibration

Generally, it is recommended to perform the calibration (meaning user calibration using the calibration board) regularly in given time intervals, every time the device is transported, after a significant change of ambient temperature or change of scanner optics. Based on an internal inspection procedures, the system is able to autonomously point out to the user that the scanner is probably not calibrated, and that it is necessary to perform the calibration. When the scanner is used in a laboratory with stable conditions and the system does not warn about the necessity to calibrate the device, the circumstances tempts the user to not perform the calibration very often.

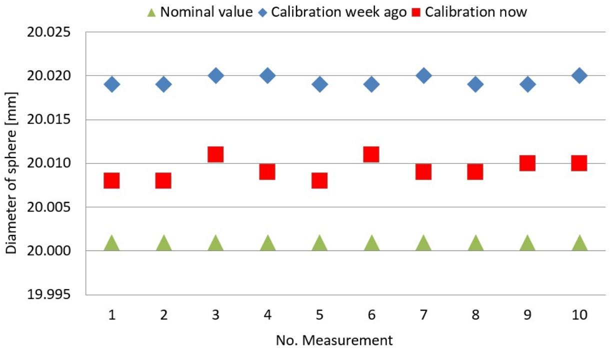


Figure 10. Effect of calibration on sphere diameters (MV 250, measurement series No. 1)

During the first experiment, where the aforementioned methods were used, we performed an etalon digitisation and evaluation of parameters such as sphere diameters and spacing. The measurement was performed using procedures for first series (part 4.2) and MV 250 measuring volume. First, the digitisation was performed on a device, whose calibration period expired approximately a week before. However, the device was in stable laboratory conditions for that time and was occasionally used for measurement. There was a total of 5 measurements. Then, a new user calibration of the device was performed, and consequently, the digitisation process was repeated five times. Results for various sphere diameters are shown in Fig. 10, spacing is shown in Fig. 11.

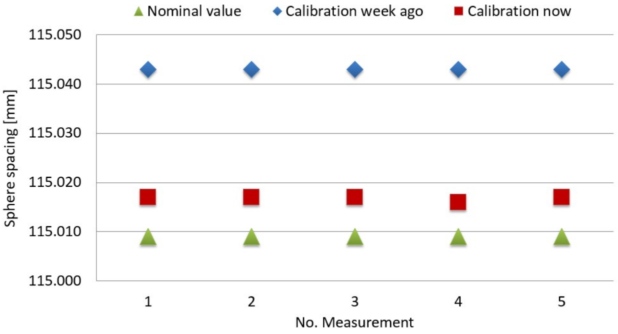


Figure 11. Effect of calibration on spacing of spheres (MV 250, measurement series No. 1)

The measured values clearly show that the results of all measurements did not fluctuate in any of the cases – the values were only slightly deviating from the average value. However, upon comparison of measurements before and after the calibration, the value is clearly different. After the calibration, the value was much closer to the nominal dimension. The deviation of sphere diameter (difference between sphere diameter obtained by digitisation and the nominal dimension) was approximately twice as large in case of “non-calibrated” system. In case of spacing, the error of “non-calibrated” system was almost four times larger in comparison to the newly calibrated device. Therefore, it is clear that in order to perform as accurate measurement as possible, it is necessary to perform calibration of the device often and regardless of the seemingly non-problematic operation of the device.

Effect of the anti-reflection coating

In the next part of the experiment, the impact of application and thickness of the matte coating was tested. The anti-reflection coating is applied manually. When regarding the shape complexity of the scanned parts, it is clear that the resulting layer will not be uniform on the whole surface. In case of our testing, two coatings were applied. During the first application, a smaller amount of powder was used, while the second coating was applied to ensure more uniform distribution and better covering.

The following graph (Fig. 12) compares diameters of left and right sphere after the first and the second coating with the nominal values. After the second coating, the average value was higher by 0.003 mm and was therefore logically further from the nominal one due to the layer of applied powder.

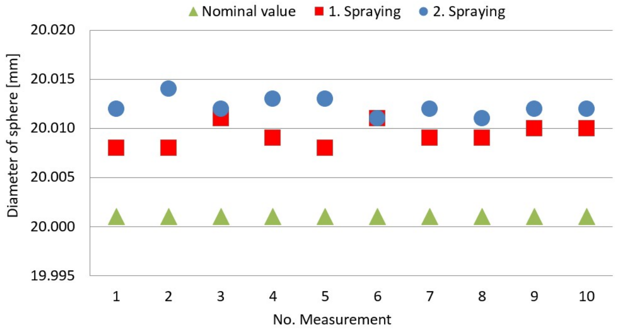


Figure 12. Effect of coating on sphere diameter (MV 250, measurement series No. 1)

The figure below (Fig. 13) proves that the quality, performance and size of coating affects the spacing only slightly (which is, in calculation principle, logical). Values measured on the sample were almost identical (coordinates of sphere centres remain unchanged).

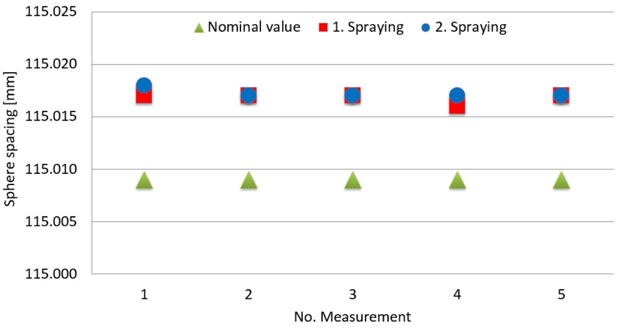


Figure 13. Effect of coating on spacing of spheres (MV 250, measurement series No. 1)

However, the quality of coating application (especially its lack) has a certain effect on the uniformity of scanned data. That is confirmed by a colour representation of deviations of the scanned sphere surface from the ideal spherical element – see Fig. 14. The figure clearly shows that when having a sufficient and well performed coating, the surface of the element is scanned more uniformly (Fig. 14 on the right), while when the matte coating is insufficient, the local reflections may cause certain irregularities of the scanned surface and lead to local errors (Fig. 14 on the left). This has a negative effect on the calculation of individual points' coordinates and decreases the measurement objectivity. In contrary to reality, this effect increases the magnitude of *Probing error form* parameter and generally increases the error of shape of the scanned elements. Therefore, the experiment shows that the anti-reflection coating must be performed not only uniformly, but with sufficient amount as well (neither too little nor too much). That however requires a very experienced operator.

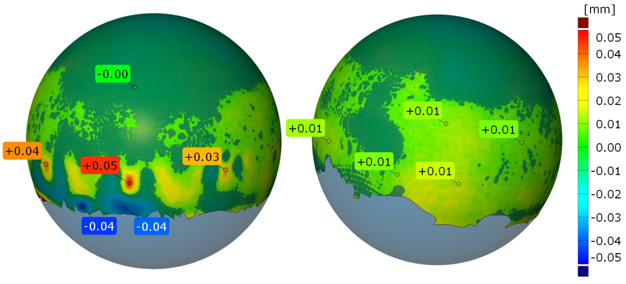


Figure 14. Deviation colour map with regard to quality of the performed coating (left – first coating {insufficient in the equator line area}, right – second coating)

5.2 *Results of the acceptance test*

The goal of our research was to try to perform a test of measurement accuracy of optical 3D scanner in research laboratory conditions using own etalon in a manner so that the performance is based on corresponding recommendations and standards and is comparable with an acceptance test performed in metrology laboratories. For this purpose a digitisation of the manufactured etalon was performed pursuant to a procedure (see part 4.2) for all 3 measurement series. Consequently, the characteristic values were evaluated. The objective was to determine all 4 determining parameters (see part 3.1) for all three measuring volumes. Using the optical digitisation, we obtained a combined total of 54 values. These values were then compared to the reference dimensions obtained by means of CMM, and the deviation was determined.

Example of evaluation for "*Probing error size*" parameter (left sphere) is listed in Table 5, the "*Sphere spacing error*" is listed in Table 6. Both evaluated for MV 250.

Measurement series	***Number of images***	***Selected points***	***Actual diameter (D_a) [mm]***	***Nominal diameter (D_n) [mm]***	***Probing error size (PS) [mm]***
1	10	2774	19.992	20.001	-0.009
2	10	2763	19.983	20.001	-0.018
3	10	2615	19.991	20.001	-0.010

Table 5. Evaluation of the "Probing error size" parameter (MV250, left sphere)

Measurement series	***Number of images***	***Actual spacing [mm]***	***Nominal spacing [mm]***	***Sphere spacing error (SD) [mm]***
1	10	115.015	115.009	0.006
2	10	115.008	115.009	-0.001
3	10	115.021	115.009	0.012

Table 6. Evaluation of the "Sphere spacing error" parameter (MV250)

In order to make final evaluation of the acceptance test, the standard states that the maximum (absolute) value of each parameter obtained during all three measurement series is the decisive one. With regard to that, the table below (Tab. 7) lists the resulting overview of all evaluated parameters of the acceptance test for three measuring volumes that were used. The table also lists magnitudes of errors identified during the last test in an official metrology laboratory.

Parameter		***Results of our study***	***Metrology laboratory***
MV 55	Probing error form (sigma)[mm]	0.002	0.001
	Probing error size [mm]	0.023	0.003
	Sphere spacing error [mm]	-0.005	-0.002
	Length measurement error [mm]	0.018	0.003
MV 250	Probing error form (sigma)[mm]	0.003	0.004
	Probing error size [mm]	-0.018	-0.020
	Sphere spacing error [mm]	0.012	-0.017
	Length measurement error [mm]	-0.018	-0.035
MV 700	Probing error form (sigma)[mm]	0.009	0.024
	Probing error size [mm]	-0.087	-0.103
	Sphere spacing error [mm]	0.012	-0.044
	Length measurement error [mm]	-0.080	-0.187

Table 7. Comparison of obtained maximal values with the values provided by the manufacturer

The comparison clearly shows that in case of MV250, the obtained error values were comparable with the test performed in GOM laboratories, in case of MV700, the results were even better, but conversely, the results were slightly worse with MV55. However, it shall be noted that in all cases, the errors are in orders not higher than hundredths of mm. This proves that the system is measuring properly and that all the elements of the system (board for user calibration, cameras, and projector), measurement conditions and evaluations methods are fine. Also, it can be said that the methodology and the procedures listed in the paper are valid and generally applicable for similar systems.

In terms of official acceptance test, the values of determined deviations are compared to the limit values provided by the manufacturer. If all the parameters are below the determined limit, an Acceptance Test certificate is issued stating that the device has passed. In case of our test, we maintained to keep below the known limits in all cases. An example of known limits for MV 250 is listed in Tab. 8.

Parameter	***Results of our study***	***Limit***
Probing error form (sigma)[mm]	0.003	0.007
Sphere spacing error [mm]	0.012	0.020

Table 8. Comparison of measured maximum values with the manufacturer's limits

All the measuring volumes we used met the expectations. The measured data show capability of the scanner to scan smaller objects (their volume is a fraction of the cameras' measuring volume) and larger distances through the measuring volume area. Scanning in three measurement series proved that the ATOS scanner is able to scan objects with identical accuracy in various mutual positions.

6 CONCLUSIONS

This paper presented methodology for evaluating eligibility and accuracy of measuring by means of optical contact-less systems. It is a rather complicated process, during which many procedures have to be followed. The progress and procedure of the measurement used for verifications of the scanner accuracy is defined in so called Acceptance Test. So far, this test is the only possible way to numerically express accuracy of the ATOS optical measurement system. The test is based on VDI/VDE 2634 - part 3 standard, which is currently the only general recommendation on how to evaluate accuracy of optical systems. By respecting the parameters defined by the standard, it is possible to determine with what accuracy the scanner operates.

In terms of our research and verification of this methodology, an own calibration etalon was designed and manufactured, providing with the possibility to determine accuracy of ATOS II 400 optical 3D scanner. Additionally, the etalon was used to perform many experiments. For example, it was used to examine the effect of calibration and matte coating on the accuracy of digitisation. It turned out that even a seemingly well calibrated system may not be measuring entirely accurately, if the last calibration was performed a while ago. In order to achieve the highest possible measurement accuracy, the calibration should be performed as often as possible. Additionally, an increased attention should be paid to the uniformity and sufficiency of anti-reflection coating, since insufficiently matt surface may result in increase of noise and shape error of the inspected elements.

The priority of our research was to perform so called acceptance test of ATOS contact-less 3D scanner. All the parameters given by the aforementioned standard were successfully evaluated in all measuring volumes, leading to determination of measurement accuracy of the device in laboratory conditions. All observed parameters were below the limits given by the manufacturer. It can therefore be stated that in terms of this test, the mentioned system passed and measured within the declared accuracy. Additionally, the measurement proved that even in local conditions, it is possible to achieve results similar to those provided by an approved laboratory.

An own measurement cannot of course substitute a test performed in a certified metrology laboratory, it however provides with a possibility to perform the scanner eligibility test more often. That might save considerable amount of financial resources, since the official price of an acceptance test is very high. Nevertheless, the most important fact and output of this research is the possibility to use an approved etalon in terms of many other tests and experiments with the goal to verify the measurement capabilities of a scanner in various conditions. Therefore, we will be able to evaluate the effect of external conditions and internal digitisation parameters on the accuracy of measuring by means of contact-less 3D optical scanners. In a further study is planned also to evaluate different optical systems (scanners from other manufacturers) using the same etalon and methods, in the same conditions and to compare accuracy of measuring of different systems with each other as well as to compare with the values declared by the manufacturer of the systems.

ACKNOWLEDGEMENT

This publication was written at the Technical University of Liberec as part of the „Project 21130 - Research and development in the field of 3D technology, manufacturing systems and automation" with the support of the Specific University Research Grant, as provided by the Ministry of Education, Youth and Sports of the Czech Republic in the year 2016.

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