# ANALYSIS OF MEASUREMENT ACCURACY OF CONTACTLESS 3D OPTICAL SCANNERS

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Currently, the conventional measuring methods in industry are more and more substituted with new methods, where the inspected component is firstly digitised by means of so called optical 3D scanners, and the inspection of dimension and shape precision is performed on the obtained virtual model. This approach bears many advantages and, in many cases, provides faster and more objective results. On the other hand, it has its restrictions – for example a problematic digitisation of detailed elements such as sharp edges or small and deep holes. Also, precision of this approach is often not possible to clearly quantify and we have to find satisfaction in various comparison tests. This article familiarises its readers with the results of research focused on analysis of precision when digitising shape elements by means of 3D scanners. Simultaneously, it provides knowledge about abilities of 3D scanners to capture detailed elements of the measured component and familiarises the readers with scanning limits for individual optical systems.

**KEYWORDS**

optical measurement, laser scanner, 3D optical scanner, 3D digitization, accuracy

## 1 INTRODUCTION

Currently, the measurement of dimensional and shape precision in industrial practice is performed by conventional methods such as contact method using coordinate measuring machine (hereinafter as CMM). Although these machines provide one of the most accurate results, there is no possibility of using them in some cases. One of the possible issues might be for example measuring surfaces of complex shapes.

Due to this, laser and optical measurement systems, so called 3D scanners, are used more and more often. Compared to classic contact methods, these offer several significant advantages such as quick measuring of parts, even the complex ones, provides high data density and, most importantly, the results are independent on the stiffness of the measured part. However, the precision of this measurement method is not so apparent. Generally, there are no strictly set specifications of measurement uncertainty for optical 3D scanners. The manufacturers of 3D scanners create their own standards and verify the precision of the devices in special metrological laboratories on the etalons of ideal shapes such as spherical systems – see e.g. calibration etalon for performance of so called Acceptance Test (see Fig. 1) for optical scanners of GOM company.

**Figure 1**. Calibration etalon for so called Acceptance Test

However, we rarely reach these obtained precision values when using the scanner in regular operation, mainly due to interference and varying environment conditions.

Other research works dealing with similar topic are often focused on partial analysis or unilaterally oriented experiments. One of the first tests in this sphere have already made in 2003 [Keller 2003], who tried using non-contact measurements determine the planar dimensions of machine parts. Focus was on analysis of the origin of each error of this measurement method and on possibility of suppression of them to a minimum. Recently [Dokoupil 2013] performed an experimental identification of deviations of ATOS Triple Scan optical system during application of matting chalk coating and titanium coating. The aim of the research described in this literature is only an assessment of measurement uncertainty when repeatedly applying chalk and titanium powder and determining the layer thickness of the matting powders. Another significant research aimed at 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 of up to 44 µm, using the titanium-white-based anti-reflection coating decreases the thickness roughly tenfold – approximately to 5 µm. This has a highly significant positive influence on the precision of the digitisation process. A more detailed comparison of several scanning systems and assessment of 3D scanners precision were performed in [Barbero 2011]. In order to determine the measurement uncertainty, they performed measurement of several calibration elements such as sphere, cylinder and gage block. An expanded uncertainty of 25 µm was determined during the measurement process for Atos system. However, even in this case, the experiment was focused only on one size of measured element.

In terms of our research, we focused on complex analysis of precision when digitising by means of optical 3D scanners and on detailed mapping of the scanners' abilities to capture small elements. The analysis was performed on several laser and optical scanner often used in practice, specifically these are a ATOS II 400 contactless optical scanner and RevScan mobile scanner. The goal was to analyse the capability of scanners to operate in common practice – in non-laboratory environment, while the scanned samples are real surfaces of complex shapes and sizes.

## 2 OPTICAL SYSTEMS USED

**ATOS system** is an optical measurement system whose measurement process is based on principles of optical triangulation, photometry and Fringe Projection method

(Fig. 2). This system is used in various industrial branches such as construction, production, quality control, design, etc.

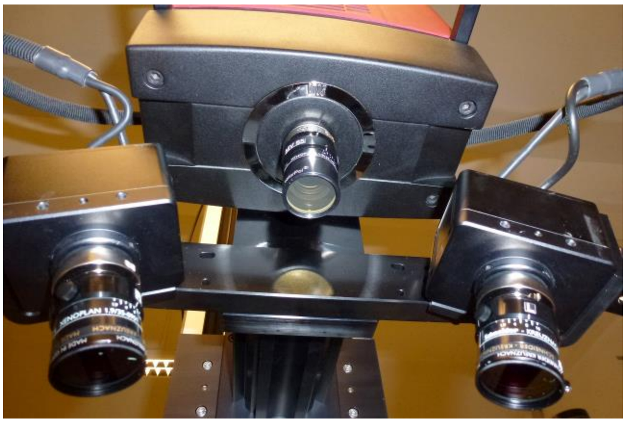


**Figure 2**. ATOS optical 3D scanner with SO measurement volume

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 the 3D area in which the measured object will be scanned – so called measurement volume. Setting the volume is not only affecting the size of the measured part, but also significantly influences the density of measured points. During the analysis, we focused on three measurement volume values as listed in Tab. 1.

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

**Table 1.** Overview of the measurement volume values for ATOS system

The **RevScan scanner** is a hand-held laser scanner allowing mutual movement of the scanner and the object during scanning (see Fig. 3). This scanner identifies reference points on the object of pad and uses two cameras to capture a laser cross on the object. The computer then shows the captured image in real time. A polygonal network is automatically generating from the object and projected laser cross. The manufacturer states a system precision of up to 0.05 mm [SilidVision 2014].

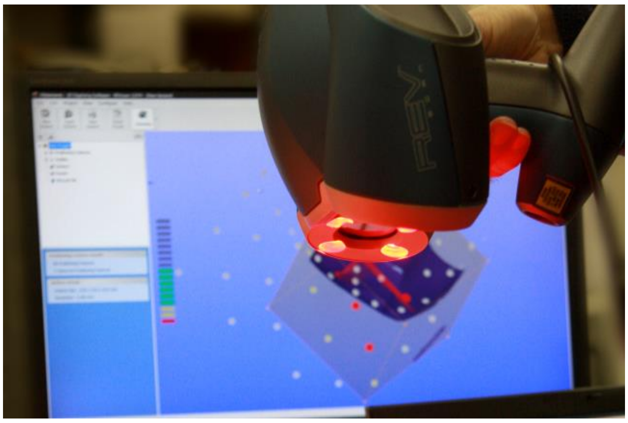


**Figure 3**. RevScan laser scanner

## 3 ANALYSIS PROCEDURE

In order to carry out the analysis, it was necessary to use an object of defined shape and dimension. Therefore, a model was design – a measurement etalon, whose part were various shape elements with appropriate dimensions. The etalon was made of aluminium alloy on a CNC machining centre (see Fig. 4).

**Figure 4**. Close look at the etalon created on CNC machining centre

Real, i.e. for nominal for our purpose, 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 precision was higher by more than an order of magnitude than the assumed measurement precision of 3D scanners. The calibration sheet states measurement precision of 2.5 µm. After the verification, multiple complete scanning of the etalon in all directions was performed. Before that, it was necessary to put reference points on the model, and due to glossy surface, to apply an anti-reflective titanium coating, or a chalk coating. All measurements were for reasons of high accuracy executed under constant conditions, namely the temperature of 20 ± 1 °C and relative humidity of 50 ± 10 %. In the next step, the scanned data were processed in the GOM Inspect Professional software by means of which the information about dimensions of the digitised etalon were obtained. A deviation was determined by comparing these dimensions obtained from the software with the values measured on CMM.

### *3.1 Measurement Etalon*

The etalon design was often based on basic shapes found on common engineering parts. Those are for example cylinders, cylindrical holes, grooves and ribs. The designed etalon consists of two parts. First part – the inner etalon surface contains elements that mostly emerge from the base. Conversely, all the elements on the bottom surface are sinking into the object (see Fig. 5).

**Figure 5**. Designed etalon – bottom side

In the first part of research, we focused on analysing the external elements – such as cylinders of various diameters, ribs, length diameters. This part of research was published in [Mendricky 2014]. Generally speaking, there is a larger problem with digitisation of internal shapes such as cavities, grooves, or other spots that are difficult to access. Therefore, in the next step, we focused on analysis of precision when scanning holes, and on determining limits of their digitisation with individual systems. The results of this research are described below.

The system of cylindrical holes used for analysis is located on the bottom side of the etalon; the holes are of several incrementing diameters (see Fig. 6). First system is located in the Figure on the left and represents two cylindrical holes with common axis and larger dimensions. The remaining holes are in four sets, while each set contains four holes of the same diameters and various depths (0.5; 1; 2; 4 mm). That way, it was possible to observe the dependence of the scanned hole depth on its diameter.

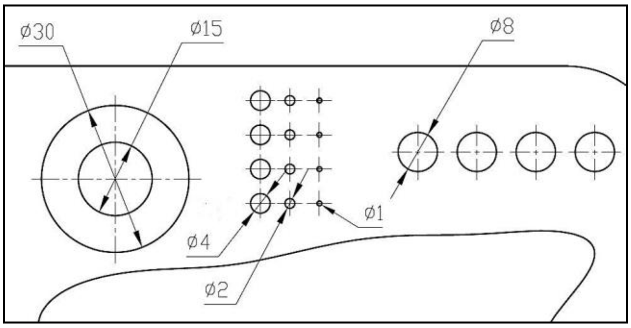



**Figure 6**. Hole diameters

### 3.2 *Digitisation of the Model*

All three lens sets were used during scanning of the object by means of ATOS II optical scanner. Each of the lenses has a different resolution and defines different measurement volume. In case of the RevScan hand scanner, the measurement volume is modified by software and its size influences the resolution of scanned data.
After the scanning, the obtained data were evaluated in the GOM Inspect Professional software. Diameters of the holes were measured by interlacing the fitting elements by Gauss best-fit for 3σ (see Fig. 7).

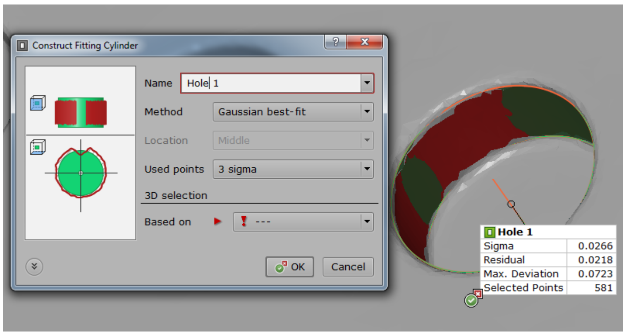



**Figure 7**. Construction of fitting inner cylinder (hole)

The scanning of the etalon was performed five times for both devices. For each dimension, an arithmetic mean and measurement uncertainty was calculated. The subject of the scanning precision analysis was the difference between the mean value and dimensions obtained by means of CMM.

### 3.3 *Inspection of Dimensions*

The partial results of the scanned data inspection were processed to graphs. Each graph was created for a group of elements identical to cylinders with changing diameter, where a deviation of the scanned dimensions from the nominal one is highlighted for all the monitored dimensions. Furthermore, an upper and lower limit of the interval of this deviation is indicated in the graph. Those were created by deduction of nominal dimension from possible maximum and minimum range of the scanned dimension that were determined from the standard uncertainty of Type A measurements. The listed limits enable estimating the repeatability of dimension measurement by means of scanners. Graphical display also enables identifying the deviation trend for the varying dimensions.

Scanning of the internal geometry was, in case of optical scanners, more problematic in general, which was confirmed even in our case. The whole group of five various hole diameters could be measurably scanned only with SO and 250 lens, for which the etalon was originally designed. The graphical representation of deviations for ATOS scanner with 250 mm measurement volume is shown in Fig. 8. When fitting the ATOS scanner with 700 mm measurement optics, it was only possible to measure holes with diameter 4 and 8 mm, which is the same as in case of using RevScan. Although the holes with the highest diameters were scanned, the low scanning resolution caused deformation of the cylindrical surface in lower depths. Therefore, it was not possible to interspace these surfaces with an ideal cylinder necessary for measurement.

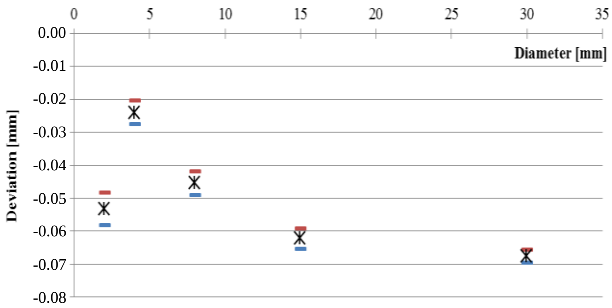



**Figure 8**. Deviations of hole diameters depending on its size (ATOS scanner – volume 250)

The trend of error development with increasing diameter for 250 lens is not behaving as one would expect. It is apparent from the graphs that with the exception of the smallest diameter, the deviation increases with the increasing diameter. Conversely, there is a positive fact that the measurement repeatability is very good. Diameters of holes scanned by the 250 lens are characterised by having the largest deviation down to -0.07 mm. Maximum deviation determined in case of SO lens was ranging down to -0.02 mm. The magnitude of deviations in case of 700 lens and RevScan scanner were noticeably worse, however, for smaller diameters, the errors should be considered with caution, since e.g. in case of 4 mm diameter, it was not possible to scan the complete cylindrical hole surface on the whole perimeter. Maximum deviation of hole with 8 mm diameter was -0.08 mm with the 700 lens and -0.18 mm for RevScan scanner. A summary of deviations range for all systems is shown on the following figure (see Fig. 9).

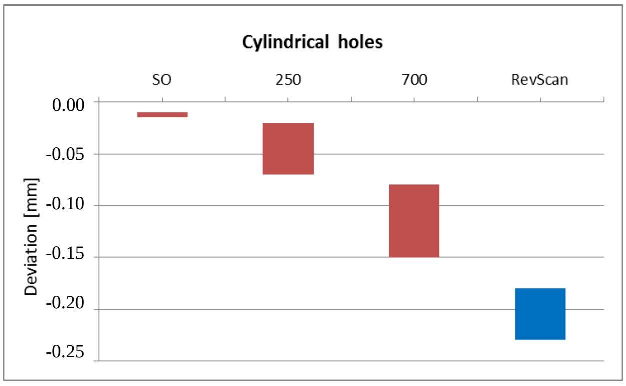



**Figure 9**. Summary of cylindrical holes diameter measurement results

When comparing these errors to the external cylindrical surfaces measuring deviations [Mendřický 2014] (see Fig. 10), it is apparent that while the external shapes are well processed by all measurement volumes of both, ATOS and RevScan scanner. Hole with smaller diameters were handled well only by ATOS system fitted with SO and 250 optics.

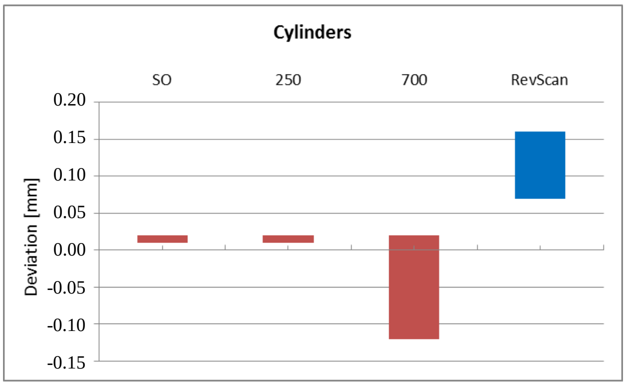



**Figure 10**. Summary of cylinder diameter measurement results

It is also worth noticing that while the external cylindrical shapes exhibited deviations of positive values, conversely, the hole errors were of negative values – smaller values were measured when compared to real ones. Based on that, it can be concluded that the magnitude of deviations may be partially affected by, among other, a layer of matting coating. If we would base our assumptions on information in [Palousek 2015] and subtracted the average thickness of the matting coating layer (a titanium powder was used in case of SO measurement volume), one could say that the precision of ATOS SO system for external and internal shapes is in the order of hundredths of mm, and for 250 measuring volume – approximately 0.03 mm. When using measurement volumes intended for large objects, lower precision is reached -0.1 mm. The worst results were provided by RevScan hand-held scanner, where the error, even after correction by means of matting coating, was reaching up to 0.15 mm. That is significantly higher error than the value of 0.05 mm provided by the manufacturer. That, among other things, confirms that we are not always able to reach theoretical values given by the manufacturers in their marketing materials.

### *3.4 Limits of Detailed Elements Scanning*

Another part of the precision analysis was finding the limits of scanner to capture detailed elements of very small diameter. During the determination of the limits, four groups of various shapes were observed. Those were cylinders, cylindrical holes, and a system of grooves and ribs. The ability to capture small holes was observed on four holes of various diameters (1; 2; 4 and 8 mm), each with difference depths. The perspectives of evaluating the ability to capture was defined by three states – completely scanned (a state, where the holes were mostly unbroken cylindrical surfaces through the whole perimeter), partially scanned (includes cases, where the cylindrical surface is sufficient for determining the diameter, however, it is incomplete or partially deformed due to adverse creation of polygonal network on insufficient number of scanned points), and not capture (which is a state, where the holes were not captured, or their diameter was not measured) (see Fig. 11).

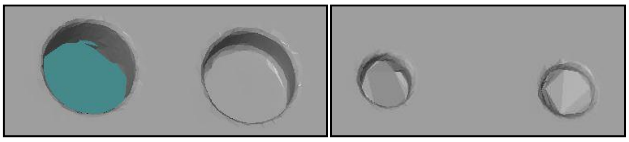


**Figure 11**. From the left: Part of the cylindrical wall, complete hole, deformed holes

The set of holes was successfully scanned only when using the SO lens, which, however, still had trouble capturing the smallest diameter of 1 mm. Conversely, the 700 lens and the RevScan hand-held scanner were able to digitise holes with size of up to 8 mm. The limits are summarised by the graph in the following Figure (Fig. 12).

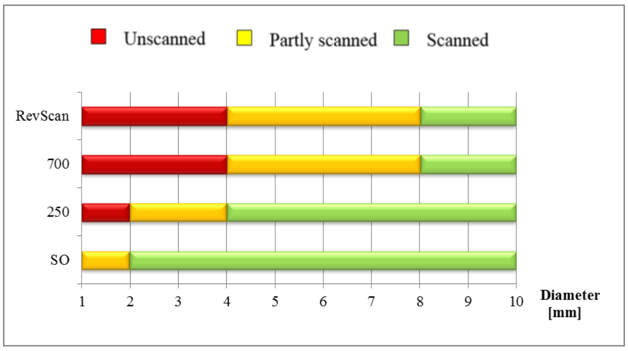
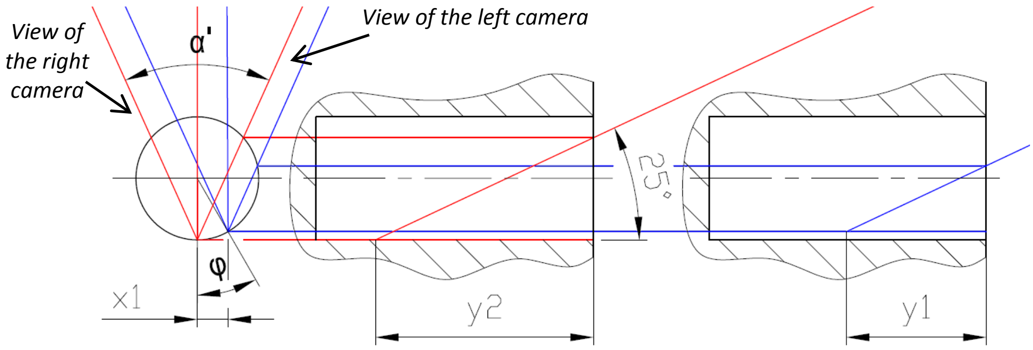



**Figure 12**. Ability of scanners to capture cylinders with small diameter.

As previously said, one of the main disadvantages of optical 3D digitisation is the inability to capture deeper parts of a hole. The reason for that is the necessity to aim at the scanned surface under a certain angle (approximately 25° based on own experience). In addition, it is necessary from the measurement principle for the same spot to be within the projector's point of view, as well as one (ideally both) of the two cameras. An analysis as well as derivation of a relation of dependence of the scanned hole depth on its diameter was performed. It was based on an assumption that the sight of cameras on the cylindrical wall is limited by a circular shape when capturing the hole, and it is therefore possible to capture only a part of a cylindrical wall resembling the surface of parabola at one image capture. By means of graphical analysis, points forming a border of this scannable image were found. This image was then unfolded to a planar surface. In the next step, it was necessary to set a number of scans by means of which the cylindrical surface was to be captured through the whole perimeter. The result of proportion of the hole perimeter and the number of scans define the part of the unfolded image stating, to what depth is it possible to completely scan the cylindrical surface (see Fig. 13).



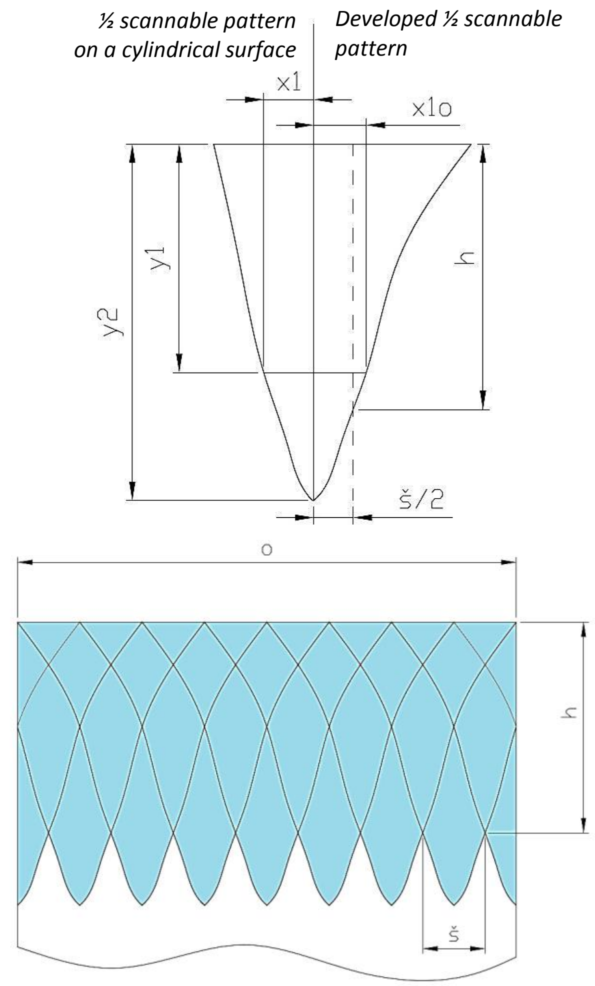




Figure 13. Excerpt from the graphical analysis of hole scannability

The more images are used to scan the hole around its axis, the more surface will be captured. The shown case is designed for capturing by means of 8 scans by ATOS II scanner fitted with 700 lens.

$$x_{10} = \frac{d}{2} \cdot \varphi \quad (1)$$

$$o = \pi \cdot d \quad (2)$$

$$\check{s} = \frac{o}{number\ of\ scans} \quad (3)$$

| | |
|---|---|
| α' | tilted angle of cameras |
| d | hole diameter |
| o | hole perimeter |
| $x_{1o}$ | arc length |
| š, h | surface dimensions of one scan, forming a part of complete scanned surface |

Graphical analysis was performed for all devices used. The determined relations are listed in Tab. 2.

| | SO | 250 | 700 | RScan |
|---|---|---|---|---|
| Cameras angle α | 24° | 31° | 22° | 29° |
| h / d (for 8 scans) | 1.2 | 1.0 | 1.3 | 1.1 |

Table 2. Dependence of the scanned hole depth on its diameter

## 4 CONCLUSIONS

The article introduced the part of the precision analysis of measurement by means of ATOS II and RevScan contactless 3D scanners. A measurement etalon was designed and manufactured, especially for the purpose of this analysis. Its nominal dimensions were determined by measuring on the coordinate measuring machine. A digitisation process was then performed, which was based on experience to obtain as complex digital model of the scanned sample as possible. The elements created in GOM Inspect based on the obtained models were compared to the real dimensions obtained by means of the CMM. By that, deviations of scanned and nominal dimensions that expressed the precision of digitisation performed by a given scanner were determined. Based on the evaluation of results, diagrams of measurement precision of scanners were drawn according to the studied aspects, e.g. dependence on the shape of the measured element and its nominal size.

The research results should help performing digitisation in common practice. Its purpose is to provide with information about possible deviation of dimensions occurred during scanning some of the basic elements. The outputs of this work may be used as a lead for choosing a proper optical device for digitising detailed elements. Also, before own digitisation, it is possible to determine based on the analysis described in the article, what is the maximum depth of internal surfaces that can be successfully scanned with the given device. Results stated in this article offer great benefits for practice, since it demonstrates the quality and limits of measuring by means of contactless optical systems in real conditions and therefore its possible use in the field of inspecting the dimensional and shape precision of industrial products.

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**REFERENCES**

**[Barbero 2011]** Barbero, B. R., Ureta, E. S. Comparative study of different digitization techniques and their accuracy. Computer-Aided Design [online]. 2011, vol. 43, č. 2, s. 188-206 [cit. 30/06/2015]. ISSN 00104485. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0010448510002150

**[Dokoupil 2013]** Dokoupil, F. Determination of the measurement error 3D optical scanner. Brno, 2013. Thesis. Brno university of technology. Faculty of mechanical engineering. (in Czech).

**[Hofman 2013]** Hofman, M. Analysis of accuracy of 3D digitizing using optical scanners. Liberec, 2013. Thesis. Technical University of Liberec. Department of Mechanical Engineering. (in Czech).

**[Keller 2003]** Keller, P. Contactless measurement of flat dimensions using digital image processing methods. In. XIV. gemeinsames Wissenschaftliches Kolloquium TU Dresden - TU Liberec, TU Dresden, Germany, pp. 7- 12, ISBN 3-86005-371-X. (in Czech)

**[Mendricky 2014]** Mendricky, R. Precision Analysis of Optical 3D Digitisation of Shaped Elements. In. Applied Mechanics and Materials, Vol. 693 (2014), Trans Tech Publications, Switzerland, p. 177- 182, ISSN 1660-9336.

**[Palousek 2015]** Palousek, D. et al. Effect of matte coating on 3D optical measurement accuracy. Optical Materials. Vol. 40, 2015. pp. 1-9. ISSN 0925-3467.

**[SilidVision 2014]** 3D Scanners. SolidVision [online]. [quote 30/06/2015]. Available on: http://www.solidvision.cz/download/pdf/handyscan.pdf

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