INFLUENCE OF THE MATERIAL ON THE ACCURACY OF OPTICAL 3D DIGITALISATION

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In recent years, optical digitalisation is increasingly being used for the inspection of the dimensional qualities of parts. Different products from various materials used in 3D printers are scanned - metal, plastic, composite or special materials. The surface may be of a different colour or roughness, may be glossy or matte. Practice suggests that the surface properties of the scanned part can significantly affect both the ability to scan and the quality of the obtained 3D model. This paper introduces research that is aim at and motivated to assess the impact of different workpiece materials on the accuracy of optical non-contact 3D digitalisation. For these purposes, almost thirty samples of different materials, colours and surfaces were produced. Scanning was performed using generically different optical 3D scanners – the Atos II and Atos III TripleScan. The data obtained from the digitalisation was assessed based on the percentage scanning of the surface and, in terms of the dimensional characteristics, a total of five different dimensions. The results obtained when scanning the samples with and without using an anti-reflective coating were compared. The research has shown that some materials, especially used in the additive production, are seemingly well-scannable, but the dimensional values are distorted.

KEYWORDS

Optical 3D Digitalisation, Fringe projection sensor, Contactless 3D Scanners, Material Effect, Digitalisation Accuracy, Antireflection Spray.

1 INTRODUCTION

Laser or optical measurement systems, so-called 3D scanners, are increasingly used today with the quality control of parts. Using them, the part to be checked is first digitalised and the actual inspection is carried out on the obtained virtual model. The control of these systems has several important advantages, such as fast measurement and complex parts, providing high data density and, above all, independence of the results on the stiffness of the component. Thanks to the overall description of the component being measured, it also allows for comprehensive and objective analyses. However, the accuracy of these measurement methods is not quite obvious. Since this is an optical principle of scanning, the main role is played by the optical properties of the measured surface. That is why we were interested in whether the accuracy of the acquired data is influenced by the material and the colour of the measured component.

There is not much described about the problem's solution in the literature available. C. Bernal [Bernal 2013] and his team investigated the accuracy of the Comet L3D measurement system using adhesive tape instead of an anti-reflective coating. They measured a white opaque strap with a thickness of 0.06 mm compared to a white powder treated object. D. Palousek and his colleagues [Palousek 2014] in his article describe the problems that can occur when scanning without the use of antireflection sprays, while explaining when to use spraying. Since the spraying manufacturer gives very precise measurement conditions (temperature, lighting and experienced personnel), the conditions may not always be ideal and the measurement results may be affected in this way. B. Levinska [Levinska 2017] also deals with the influence of antireflection sprays on the dimensional and geometric accuracy of 3D scanning. In his research, he compares seven kinds of antireflection sprays, including the 3D Helling spray, which was also used in our research. To obtain exact data, he uses several types of precision gauges and repeated the measurements. A titanium powder with a layer thickness of up to 0.012 mm was evaluated as the least affected instrument. The aforementioned 3D Helling Spray has been placed, in terms of accuracy, a second with a layer thickness of 0.015 mm. Barbero [Barbero 2011] also performed a more detailed comparison of several scanning systems and the accuracy of the 3D scanners. To measure the measurement uncertainty, he measured the calibration elements such as sphere, cylinder and end gauge. In the experiment, the expanded measurement uncertainty for the Atos 25 µm system was detected. In 2015, a comparatively extensive self-analysis [Mendricky 2015] was carried out by measuring non-contact optical 3D scanners. It was primarily focused on the analysis of the digitalisation of the shape elements, while the ability of the 3D scanners to capture detailed elements on the measured parts was examined. Further work from the team of authors led by Martinez-Pellitero S. [Martinez-Pellitero 2018] assesses the performance and operating limits of dimensional accuracy of 3D optical scanning technology-based projections with blue light. The standard used for the research was made of a matte white ceramic material and the reference dimensions were measured on the coordinate measuring machine. In the research, the authors also analysed the effect of the scanner software on the measurement results. In addition, various tests were carried out for several measuring volumes of the sensor. The survey offers practical values and accuracy limits for individual configurations. Some interesting research on the influence of the material surface on the scanning error is described in the author's work [Course 2015]. Unfortunately, this is not an application in mechanical engineering, but materials primarily used in dentistry. However, the findings found there are important as the authors conclude that the use of different materials causes height differences in scanning. Another interesting result is that the noise in the data can be reduced by holding the scanner as close as possible to the perpendicular to the sample.

2 METHODS AND MATERIALS

For the purpose of our research, a total of 28 samples were produced, 22 of which were printed using 3D printers and the remaining 6 were made by chip machining on the KAFO KFO-620-5AX five-axis machining centre. The machined samples were made of AMPCO 22, steel 11 523, brass, aluminium, Teflon, and polyamide PA6. A total of four 3D printing technologies - PolyJet, FDM, SLA and SLS - were used for the additive technology of a sample's production. Most of the printed samples were created in a glossy and matte finish if the technology allowed it (see Figure 1).

Figure 1. The scanned samples

2.1 *The PolyJet Technology*

This technology is based on the application of individual layers of photopolymer materials, which are subsequently cured by a UV lamp. The thickness of the layer is typically in the order of tens of micrometres. A total of 14 samples were used for the Objet Connex 500 and J750. Most of the samples were made of the frequently used Vero-branded material, which differed only in colour. They ranged from black, white, blue, red-violet, ivory-coloured to almost colourless and transparent. In addition to this material, the PureWhite (No. 1 and 2) and ABS-like digital materials (No. 15 and 16) were also used.

2.2 *The FDM Technology*

FDM or Fused Deposition Modelling is a technology in which a thermoplastic is melted in the printhead, which is subsequently extruded into a substrate in the form of a thin filament. The construction is made of two materials at the same time, the support and the construction, and the support material is removed after the printing is complete. With this technology, three different samples were made from ABS black (No. 3), PC-ABS (No. 4) and ABS white (No. 14). Dimension and Fortus printers were used as the printer.

2.3 *The SLA Technology*

SLA or Stereolithography apparatus is a technology working on the principle of curing a layer of liquid polymer using a UV laser beam. With this technology, the transparent sample No. 5 was made.

2.4 *The SLS Technology*

SLS or Selective Laser Sintering is a technology that cakes material by laser. The fine powder material is applied to the worktop of the heated table and cured in the individual layers. Two sample pairs, the grey samples from the Sintratec PA 12 Powder (No. 19, 20) and the white samples from the PA 2200 (No. 27, 28) were created using the SLS method.

An overview of all the samples, including information on the production and material technology used, is given in Tab. 1.

Technology	Sa.	Machine	Material	Other
PolyJet	1	J750	PureWhite	Glossy
PolyJet	2	J750	PureWhite	Matte
FDM	3	Dimension	ABS black	Glossy
FDM	4	Fortus	PC-ABS	Glossy
SLA	5	Formlabs Form 2	Durable	-
PolyJet	6	Objet 500	VeroBlack	Matte
PolyJet	7	Objet500	VeroBlack	Glossy
PolyJet	8	J750	VeroClear	Glossy
PolyJet	9	J750	VeroClear	Matte
PolyJet	10	J750	VeroCyan	Glossy
PolyJet	11	J750	VeroCyan	Matte
PolyJet	12	J750	VeroMagenta	Glossy
PolyJet	13	J750	VeroMagenta	Matte
FDM	14	Dimension	ABSwhite	Glossy
PolyJet	15	Objet 500	ABS_like	Matte
PolyJet	16	Objet500	ABS_like	Glossy
PolyJet	17	J750	VeroGrey	Glossy
PolyJet	18	J750	VeroGrey	Matte
SLS	19	Sintratec Kit	Sitratec PA12	Matte
SLS	20	Sintratec Kit	SitratecPA12	Matte
Machine-tool	21	KAFO KFO	AMPCO 22	Glossy
Machine-tool	22	KAFO KFO	Steel 11 523	Glossy
Machine-tool	23	KAFO KFO	Brass	Glossy
Machine-tool	24	KAFO KFO	Aluminium	Glossy
Machine-tool	25	KAFO KFO	Teflon	-
Machine-tool	26	KAFO KFO	PolyamidePA6	-
SLS	27	EOSINT P 395	PA 2200	Pos. X
SLS	28	EOSINT P 395	PA 2200	Pos. Y

Table 1. The overview of the examined samples

The samples were first scanned without the antireflection spray application using two different scanners. An Atos II 400 and an Atos III Triple Scan scanner were used. These two scanning systems were used for scanning the clean samples as they use different projector lights. While the ATOS II scanner uses white light, the ATOS III has a projection unit with a blue LED illumination which, according to the manufacturer, should better deal with glossy objects (see Figure 2).

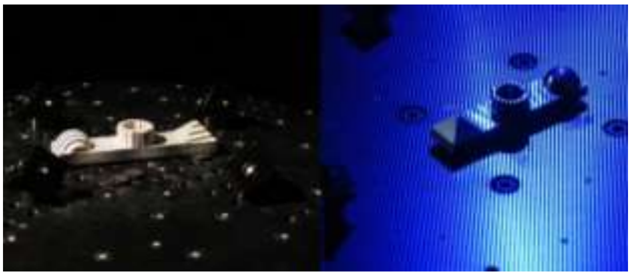

Figure 2. The scanning process (left, ATOS II - white light, right, ATOS III - blue light)

Following the scanning of the samples, a weak layer of Helling anti-reflective coating was applied. This will not significantly affect the measurement accuracy, since according to researches, it's the thickness is a maximum of one hundredth of a millimetre. The measurement procedure was identical for all the samples. Depending on the surface properties and colour of the part, the optimum exposure time was set, the samples were placed on an automatic rotary table and a total of 12 images were scanned for 30°, the scanner was rotated at an angle of 45° to the horizontal plane of the table. These sub-scans were transformed into a common coordinate system by the software and an optimised polygonal network - the so-called Mesh (STL file) - was generated. This was subsequently processed in the SW GOM Inspect Professional, in which the required dimensional characteristics were measured - the outer and inner diameter of the cylindrical element, the diameter of the ball and the dimensions of the sample base X and Y (see Figure 3).

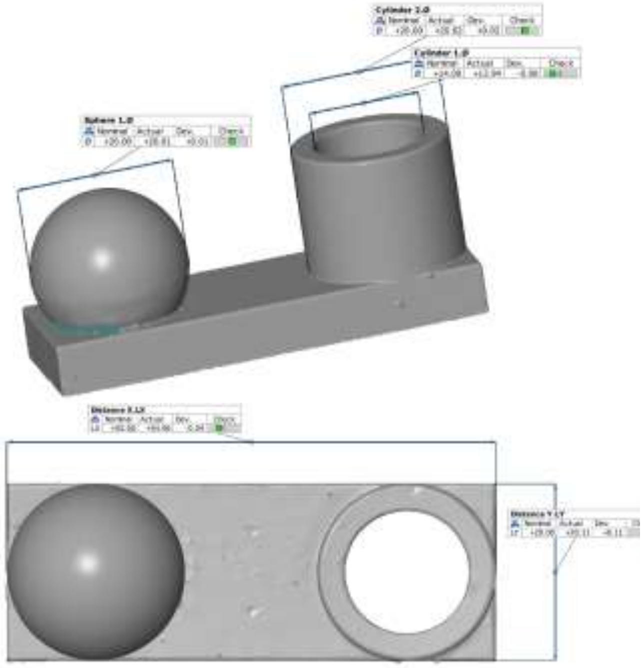

Figure 3. The measured characteristics

"Gauss's Best-fit" was chosen as the method of calculating the entities, using 3 (i.e., 99.73%) selection points to calculate the element (see Figure 4).

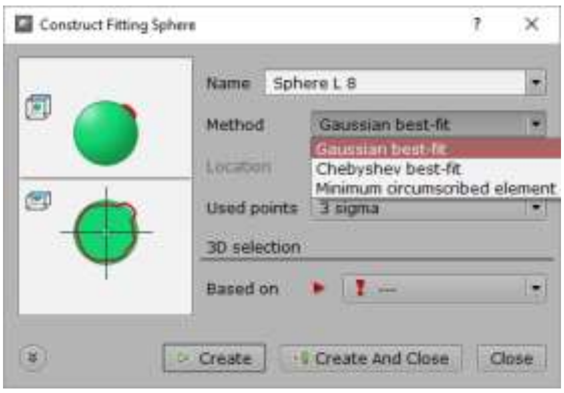

Figure 4. Construct Fitting Sphere

The dimensions calculated by this procedure were then compared with the data measured on the coordinate measuring machine. Specifically, it was a DEA, Global model 07.10.05. According to the manufacturer's specification, the accuracy of this machine is MPEE = 2.5 + L / 333 µm, MPEP = 2.5 µm. These values are confirmed by the machine calibration sheet. Given that these values are about one order more accurate than the accuracy of the scanning systems, the dimensions obtained by the CMM measurements are considered as reference - nominal.

3 THE RESULTS OF THE MEASUREMENTS

The evaluation of the samples was carried out according to two main criteria, according to the percentage of the scanned surface and the accuracy of the measured dimensions. By combining the results, it was possible to determine which materials can be scanned without the use of sprays, without distorting the scanned data. Several groups of materials emerged from this division.

Three groups were identified for the distribution of materials according to the scannability of the surface (see figure 5):

- Non-spray non-scanned materials, where the scanned surface was up to 50%
- Materials that are partially scannable, the scanned surface of which ranged between 50-80%
- Materials that can be scanned where the percentage of scanned area exceeds 80% of the surface.

Figure 5. Percentage of the scanned surface (up to 50%, 50-80%, more than 80%)

3.1 *Non-spray non-scanned materials (up to 50%)*

For the Atos II, it was non-scannable or scannable to such a small extent that it was impossible to create a mesh, it showed a large number of samples, namely 11, of which 5 samples were made on 3D printers and the other 6 samples were machined. The percentage of scans ranged to 12% of the surface of the printed samples. The machined specimens were even worse, the aluminium and Teflon samples were not scanned at all, and the other four samples were digitalised with small segments, roughly up to 1% of the surface.

For the newer Atos III, six samples appeared as non-scanned. 3 printed ones (samples No. 5, 8 and 9) and 3 machined ones (No. 21, 22 and 25). The scanning percentage for some of these samples reached up to 36% of the surface (see Figure 6).

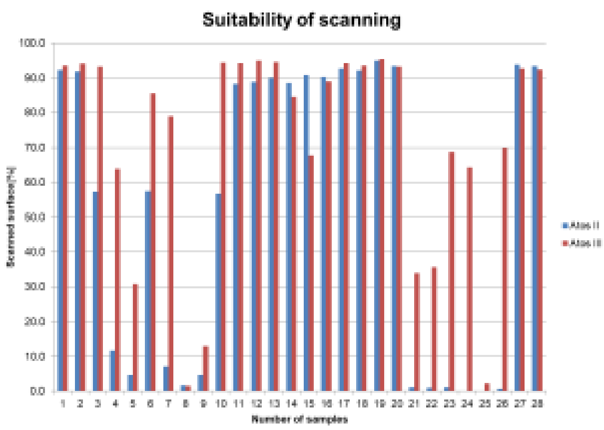

Figure 6. Suitability of the scanning

3.2 Partially scanned materials (50-80%)

Among the materials with scanning ranging from 50 to 80% of the surface, the Atos II scanner had three samples, namely No. 3, 6 and 10, where all the samples were scanned to approximately 57% of the surface.

For the Atos III scanner, the group of partially scannable samples was a bit more numerous, as three printed samples and three other processed samples were added to this group. The percentage of the scanned area, in this case, ranged between 60 and 80% of the surface. The highest scanning percentage was achieved by the PolyJet VeroBlack No. 7 in a glossy finish of 79%.

3.3 Materials that can be scanned (more than 80%)

14 and 16 samples were successfully scanned for more than 80% for the Atos II and for Atos III, respectively. The scanned surface ranged between 88.3-95% for the Atos II and between 84.6-95.4% for the Atos III.

	Non-scannable (up to 50%)	Partially scannable (50 – 80%)	Well scannable (more than 80%)
ATOS II	11	3	14
ATOS III	6	6	16

Table 2. The number of samples per group

Comparing both scanning systems with the ability to scan the surface without the need for chalk powder treatment, it can be stated that in terms of the number of scanned samples, the newer Atos III system is better, scanning more than 50% of the surface in 22 samples, whereas the Atos II only scanned 17 of the 28 samples. The difference was mainly the glossy machined samples that the older ATOS II system did not successfully match with any one.

Another parameter of the evaluation was the accuracy of the scanned dimensions for non-surface samples. Two groups were identified here:

- Scannable materials with poor dimensions
- Scannable materials with good dimensions

3.4 Scannable materials with poor dimensions

The sample data, which belongs to groups that are partially scannable and well scannable, has also been evaluated in terms of dimensional characteristics. The individual measured dimensions (see Figure 3) of the samples scanned without an anti-reflection coating (for ATOS II and ATOS III) and the dimensions of the identical samples scanned after the application of the anti-reflection layer (for ATOS II) were always compared with the reference dimensions from the coordinate measuring machine. The calculated deviations are plotted in the following figures graphically for each of the monitored elements. To increase objectivity, the dimensions obtained from the chalk of the modified samples were corrected with the theoretical thickness of the chalk spray, which was chosen based on previous studies (e.g., [Levínská 2017], [Paloušek 2015]) with the size of 0.015 mm.

The first of the verified dimensions was the diameter of the inner cylinder. After the anti-reflection treatment, the inner diameters usually appear smaller than they actually are, due to the thickness of the layer on the sample being scanned. This was corrected for 0.03 mm for evaluation purposes.

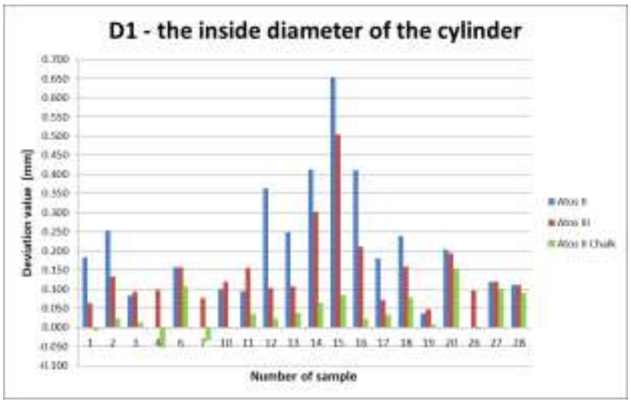

Figure 7. D1, the inside diameter of the cylinder

It can be seen from the graph in Figure 7 that the precision of the values without the surface treatment is not very convincing for one of the scanners. The smallest deviations from the chalked data reached the sample printed by SLS No. 27 and 28 with a value of 0.020 mm. On the other hand, sample No. 15 from the PolyJet technology was the worst hit with the ABS_like material with a matte finish with a 0.57 mm and 0.42 mm deviation for the Atos II and Atos III, respectively.

Another dimension that was analysed in the research was the outer diameter of the cylinder.

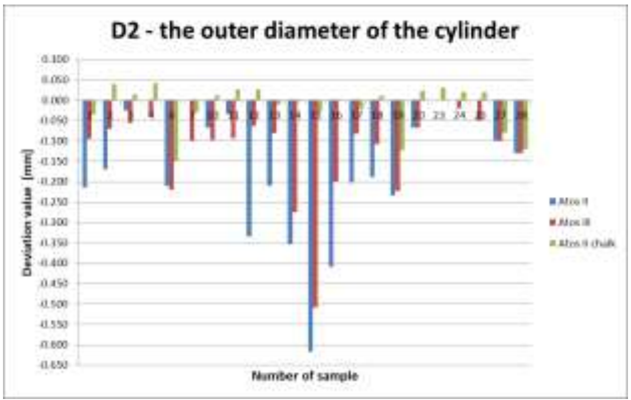

Figure 8. D2, the outer diameter of the cylinder

It can be seen from the graph in Fig. 8 that if the surface is not coated with the anti-reflection spray, many scanners will not be able to handle the materials if we scan the external shapes. When determining the deviations of the outer diameter of the cylinder, very similar results were obtained, only deviations of the opposite sign were obtained. The smallest error between the non-chalked and the chalked sample was again achieved on sample No. 28, identical for both scanners of -0.01 mm. The second most accurate result was sample No. 27 with a 0.02 mm deviation. The worst was sample No. 15 with deviations of 0.59 mm (Atos II) and 0.48mm (Atos III), respectively.

Similar results were obtained from the analysis of the other observed parameters, i.e., the diameter of the sphere, the length of the model in the X-axis and the Y-axis length (see Figures 9, 10, and 11).

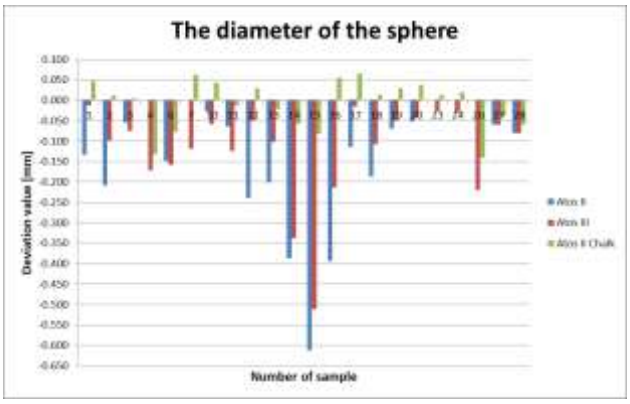

Figure 9. The diameter of the sphere

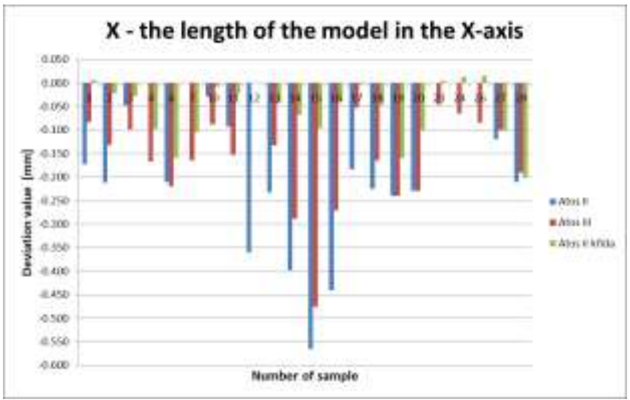

Figure 10. X (the length of the model in the X-axis)

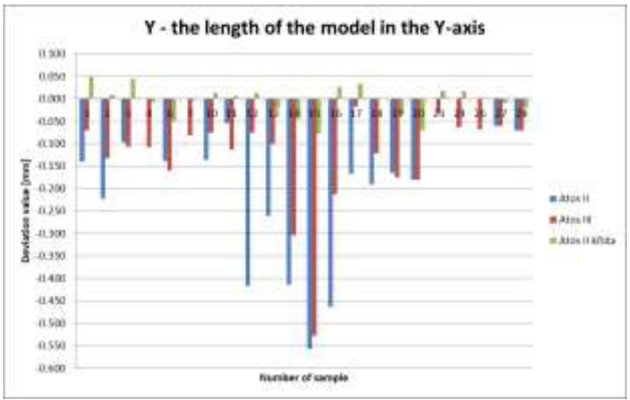

Figure 11. Y (the length of the model in the Y-axis)

4 DISCUSSION

The above results confirm that the material and workpiece colour depend more on the shape being scanned. For all four observed external dimensions, comparable results were obtained, both for the samples measured without modification and for the chalked samples. At the same time, the assumption was made that the samples provided with the matte spray were, in most cases, scanned with much higher accuracy. Since the measurement results on the coordinate measuring machine may not always be relevant for certain shapes, when comparable to optical scanning on 3D scanners, another issue has been raised. The differences between the dimensions detected by scanning the clean samples and the dimensions of the chalk samples were calculated and averaged and graphically processed for all four outer dimensions (cylinder outer diameter, ball diameter, length X and length Y). The results worked out in this way for both systems are shown in Figure 12. This analysis, at first glance, better illustrates how large errors are made if the optically inappropriate surface is scanned without chalk spraying. If there is no deviation for ATOS II for a sample, the column does not mean that the error is zero, but the sample was not scanned by the system without being scanned from the dimensional point of view.

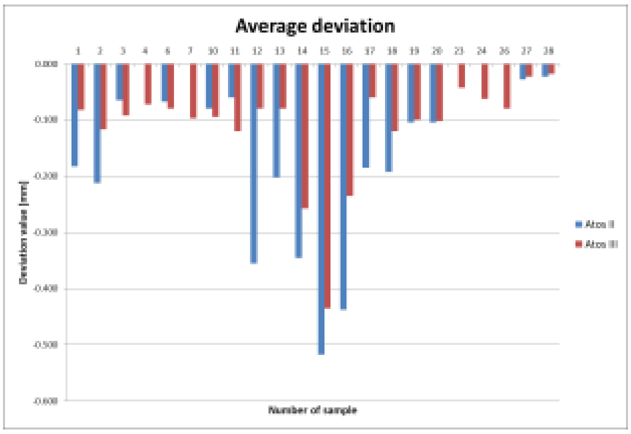

Figure 12. The average deviations of the external elements between the non-chalked and chalked samples

From the results, it can be seen that, for example, sample No. 15 is scanned with an average deviation of 0.52 mm for the outer dimensions (Fig. 12) and 0.57 for the internal dimension (Fig. 7) (ATOS II), provided it is not controlled. This means that the scanner did not scan the actual sample surface, but an apparent offset of about 0.27 mm into the material. Thus, although the percentage of the scanned surface has reached 90.9%, it can be stated that the ABS-like material in the matte finish is not scannable without the surface treatment with the anti-reflective coating. Similarly, ABS is a glossy finish (sample No. 16) when a 0.22-mm-thick surface is captured by the scanner or a white ABS-white gloss pattern (sample No. 14) with a 0.17 mm normal error.

By the Atos III scanner, the wrong dimensions were measured for the same samples as the first scanner, only the inaccuracy measured was smaller. As the least accurate, sample No. 15 was shown, where the surface was scanned about 0.22 mm beneath the actual surface. In addition, with less than 68% of the scanned surface, this sample was classified as partially scanned. Another material scanned under the surface was ABS white (sample No. 14), whose normal deviation was approximately 0.13 mm.

Taking all the factors that affect the accuracy of digitalisation into account, we can correctly mark those materials that do not need to be provided with an anti-reflection layer, at least over 50% of the surface being scanned (a mesh can be created without difficulty) the dimensions are within a maximum of 0.1 mm, i.e., the inaccuracy is up to 0.05 mm on each side. This criterion will result in only 8 samples from 28 for the Atos II, which can be labelled as accurately scannable with dimensions corresponding to reality. The most accurate samples are highlighted in green, while the samples are scannable, but without the spray and with bad dimensions, then they are red in the following table.

Sample No.	Difference D1	Difference D2	Difference Sphere	Difference X	Difference Y	Average deviation
1	0.190	-0.180	-0.180	-0.180	-0.190	-0.183
2	0.230	-0.210	-0.220	-0.190	-0.230	-0.213
3	0.070	-0.040	-0.060	-0.020	-0.140	-0.065
6	0.050	-0.060	-0.070	-0.050	-0.090	-0.067
10	0.100	-0.080	-0.070	-0.020	-0.150	-0.080
11	0.060	-0.060	-0.050	-0.070	-0.060	-0.060
12	0.340	-0.360	-0.270	-0.360	-0.430	-0.355
13	0.210	-0.200	-0.180	-0.190	-0.240	-0.202
14	0.350	-0.350	-0.330	-0.330	-0.370	-0.345
15	0.570	-0.590	-0.530	-0.470	-0.480	-0.517
16	0.390	-0.410	-0.450	-0.400	-0.490	-0.438
17	0.150	-0.180	-0.180	-0.180	-0.200	-0.185
18	0.160	-0.200	-0.200	-0.180	-0.190	-0.193
19	0.030	-0.110	-0.100	-0.080	-0.130	-0.105
20	0.050	-0.090	-0.090	-0.130	-0.110	-0.105
27	0.020	-0.020	-0.020	-0.020	-0.050	-0.028
28	0.020	-0.010	-0.020	-0.010	-0.050	-0.023

Table 3 - Atos II – The deviations of the samples

For Atos III, as shown in Table 4, the samples with dimensions approximating reality were twice as many, i.e., 16, but for example, for samples No. 23 and 24, the inside diameter of cylinder D1 was not scanned so that even though the sample was evaluated as being capable of being scanned without the spray, application of the antireflection coating would be necessary in order to obtain the dimensions of the internal openings and holes.

Sample No.	Difference D1	Difference D2	Difference Sphere	Difference X	Difference Y	Average deviation
1	0.070	-0.060	-0.060	-0.090	-0.120	-0.083
2	0.110	-0.110	-0.110	-0.110	-0.140	-0.118
3	0.080	-0.070	-0.080	-0.070	-0.150	-0.093
4	0.090	-0.080	-0.040	-0.070	-0.100	-0.073
6	0.050	-0.070	-0.080	-0.060	-0.110	-0.080
7	0.110	-0.070	-0.180	-0.060	-0.080	-0.098
10	0.120	-0.110	-0.100	-0.080	-0.090	-0.095
11	0.120	-0.120	-0.110	-0.130	-0.120	-0.120
12	0.080	-0.090	-0.080	-0.060	-0.090	-0.080
13	0.070	-0.070	-0.080	-0.090	-0.080	-0.080
14	0.240	-0.270	-0.280	-0.220	-0.260	-0.258
15	0.420	-0.480	-0.430	-0.380	-0.450	-0.435
16	0.190	-0.200	-0.270	-0.230	-0.240	-0.235
17	0.040	-0.060	-0.080	-0.050	-0.050	-0.060
18	0.080	-0.120	-0.120	-0.120	-0.120	-0.120
19	0.040	-0.100	-0.080	-0.080	-0.140	-0.100
20	0.040	-0.090	-0.080	-0.130	-0.110	-0.102
23		-0.030	-0.040	-0.050	-0.050	-0.042
24		-0.040	-0.050	-0.080	-0.080	-0.063
26	0.100	-0.070	-0.080	-0.100	-0.070	-0.080
27	0.020	-0.020	-0.020	0.000	-0.050	-0.023
28	0.020	-0.010	-0.020	0.010	-0.050	-0.018

Table 4 - Atos III – The deviations of the samples

5 CONCLUSION

At present, it is not possible to perform optical digitalisation of some surfaces without the use of matting products. Therefore, it is necessary to know how the individual materials behave if we scan them without this surface treatment, whether they can be scanned or not. Generally, there are three basic cases of the measured surface. The ideal one is a component that can be digitalised by optical 3D scanners without the use of matte sprays. Even without these products, the dimensions correspond to the real model. The second extreme is that the optical properties of the surface are not appropriate enough (a smooth, shiny, transparent, black surface) so that the surface is not scanned without the matting. However, the third possibility is the riskiest. These are the surfaces that the scanner even without the anti-reflection coating scans relatively easily, but the dimensions are error-prone with regards to reality. As confirmed by this research, such behaviour is most often encountered, for example, in semi-glossy (translucent) plastics, in the 3D printer models, etc. The biggest threat here is that without spraying or inadequate spraying, we get distorted results, often by a tenth of a millimetre. The measured dimensions in this case are generally smaller than reality. Without this knowledge, grave mistakes could be made in interpreting the measurement results.

Based on our research, the first group (materials whose dimensions can still be considered scannable without the anti-reflection coating without any significant distortions of the dimensional values) samples printed using the SL 22 PA 2200 can mainly be included, that without chalk coating showed very accurate results. The average difference in the dimensions scanned with and without they spray is only about 0.02 mm for both types of scanner. Acceptable variations were also achieved with the second pair of samples produced by the SLS. Also, the models made by the FDM technology (ABS black) show a relatively good match.

Completely non-scannable (thus classifiable in the second group) for the ATOS II system are mainly the highly glossy materials, for example, samples made from chipboard machining of polyamide, Teflon, aluminium, brass, steel and, of course, transparent materials made by 3D printing (VeroClear, SLA Durable) .

The PolyJet technology belongs to the third, riskiest group, of materials that can be scanned for surface capture, but the dimensions do not match reality, specifically the PureWhite and ABS like, which achieved the worst results in the experiment. For the older scanner (Atos II), the dimensions were on average smaller by 0.52 mm and on the newer scanner up to 0.44 mm smaller. Very poor results were also achieved for the ABS white for the FDM technology.

The Vero materials for PolyJet technology can be categorised outside the category, the results of which are most debatable. From the results, it is obvious that it depends on the combination of the colour of the material and the colour of the scanner light. e.g., the VeroGrey tint was not captured by a single scanner at the required tolerance, while the Vero Black captured both the correct size system. An interesting surprise was the shade of the VeroCyan, which was captured relatively accurately by the older ATOS II system, while the new glossy sample system was not scanned at all, the dimensions were out of tolerance in the matte design.

Thus, it is evident that even in modern systems operating on the optical sensing principle, it is often necessary to use anti-reflection sprays. The surface matting will unify the optical properties of the models, and according to the research, this is the only way to reliably scan optically unsuitable surfaces with guaranteed accuracy.

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