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Measurement of polymers with 3D optical scanners: evaluation of the subsurface scattering effect through five miniature step gauges

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Abstract

In this work, the interaction between 3D optical scanners and objects realized with different materials and colours was investigated. The interaction is mainly related to the translucency of some materials, such as polymers, which is a category of materials ever more demanded in industry. At the same time, the increase of the geometrical complexity of manufactured parts raises the need for using 3D optical scanners thanks to their rapidity and effectiveness. Translucency causes a subsurface scattering effect that has been modelled for certain cases and affect the dimensional accuracy of measurements, as well as, the quality of reconstruction. Recently, an investigation considered its effect in dimensional verification using a structured light scanner with fringe projection. In this work, the investigation was extended to other 3D optical scanners exploiting different measuring principles: laser, structured light based on phase shifting and gray code, and photogrammetry. This was done in order to study how the subsurface scattering effect can vary with the materials, colours, and also the measuring principle used. To this end, five miniature step gauges made of different polymers and different colours were used, and the effects due to their different optical properties investigated. The analysis focused on dimensional verification of bidirectional lengths, first calibrated with a traceable CMM. The quality of the reconstruction was also evaluated through the flatness values. According to the results obtained, translucency of materials has a dual and significant effect: a measurement bias and an increase of the uncertainty due to the different quality of reconstruction retrieved. Thus, it has to be considered properly, for each case.

Keywords: *polymers, miniature step gauges, subsurface scattering, translucency, bidirectional lengths, 3D optical scanner, photogrammetry, laser scanner, structured light scanner.*

1. Introduction

Optical based scanners offer many advantages. They are capable of acquiring a large amount of information in a short time and in a reliable way, which makes those instruments suitable for on-machine verification in manufacturing industry [1]. However, considerations regarding their accuracy and reliability are not generalizable. A certain number of error sources are known to affect optical based systems. Indeed, object material and colour can affect the accuracy of the systems in a way strictly dependent on the measuring principle adopted.

Measuring polymers with 3D optical scanners became a widely spread measuring task in many industrial fields, due to the increase of polymers used in manufacturing, for both conventional manufacturing processes, such as injection moulding [2] and the newer additive technologies [3]. Polymers, indeed, exhibit optical properties, which interact with the optical measuring system depending on the specific material, the grade, the colour and the manufacturing process in terms of surface finish [4,5]. In particular, the optical interaction is due to transmission, scattering and absorption. Generally, the scattering phenomenon plays a major part in determining optical interaction, since polymers are translucent materials having microstructural features of dimensions comparable with the wavelength of visible light ($\lambda = 0.4\text{-}0.8\ \mu\text{m}$). When a 3D optical scanner is used for measuring a polymer, the measured point will not lie on the real external shape of the object, but it will be shifted a certain amount into the interior due to subsurface scattering. Several models exist that can be used for measuring the scattering properties of translucent materials [6–8]. The entity of the phenomenon is linked to the wavelength of the light source and to the optical properties of the material. Thus, it is of fundamental importance to know those parameters for each material, colour and surface finishing considered. However, specialized equipment is needed to measure optical properties [6–8]. In this work, the quantification of the subsurface scattering was carried out using a well known reference object: the step gauge. It was realized in different materials and colours and their bidirectional lengths analysed and compared with respect to CMM values. Bidirectional lengths take into account the “probing effect”, which would represent, for non-contact measuring systems, the interaction between the measuring instrument and the optical properties of the workpiece.

2. Research background

The interest towards the optical properties of different materials, manufactured with different surface finishes, and, having different colours, is a topic of great interest, but it is not yet fully explored. National institutes for metrology developed some facilities for the characterization of several aspects affecting 3D optical instruments, and, in particular, how the materials and surface finish can affect the results in terms of number of acquired points, using specifically designed artefacts [9]. The influence of colour is investigated for a laser line scanner [10] and a commercial structured light scanner [11], considering a specific coded pattern. Both these researches use the x-rite ColorChecker chart [12], manufactured to provide a standard set of colour patches with known spectral reflectance for the photographic industry. Results confirm the expectations, and the surface colour is a factor to consider when dealing with optical-based instruments. Although, in that research, the effect of surface colours and materials on dimensional accuracy is not evaluated.

Generally, the difficulties related to digitization of translucent surfaces are overcome through different methods, such as bias correction, polarization difference imaging, modulated phase shifting, as well as matte coating of such surfaces [13]. The latter is employed to reach Lambertian conditions. However, a coating can change the overall size and the geometry of the sample, and it should always be checked with a profilometer. Moreover, it is difficult to achieve a uniform coating thickness especially if the geometrical complexity increases, and it is strongly related to operator skills and experience. This practise is widely used for large parts, where addition of a few micrometres of coating, even if not applied uniformly, does not significantly affect the accuracy and the total uncertainty [14].

Other approaches have, therefore, been developed to reduce the effects caused by subsurface scattering, and to improve the signal-to-noise ratio for structured light scanners. In particular, Chen *et al.* [15] developed a technique that combines polarization difference imaging (PDI) with structured light 3D scanning based on phase-shifting patterns to filter out subsurface scattering. PDI is an efficient tool for deblurring the phase-shifting pattern and obtaining a more robust 3D scanning of translucent materials. However, the depolarization length, that is, the distance that light needs to travel through the material before being unpolarized, is 3 to 10 mean free paths (depending on the scattering anisotropy of the material) for common translucent materials [16]. This means that while scanning may be more robust

with this technique, it does not remove the bias problem (offset due to subsurface scattering). In a follow-up work, Chen *et al.* [17] obtained even better robustness when scanning translucent materials if using modulated phase-shifting, where a one-dimensional phase-shifting pattern is multiplied by a second shifted high-frequency pattern in the orthogonal direction. However, the focus of this work is scanning robustness rather than accuracy.

In a research by Gupta *et al.* [18,19], new binary code patterns based on logical operations like exclusive-or (xor) are introduced to obtain more robust 3D scanning of scenes with global illumination effects (such as subsurface scattering). Again, the focus in this work is on obtaining a scan rather than on the dimensional accuracy of the scanned surface. Similarly, Kobayashi *et al.* [20] propose a complementary Gray code projection to improve 3D scanning based on structured light. These authors obtain more complete scans (better robustness) than the COMET5 scanner they are comparing with, but work with objects for which the true 3D shape is unknown. Thus, they too cannot investigate accuracy. Another technique for better robustness in scanning of translucent (or specular) materials is based on estimation of a homogeneous light transport matrix [21]. Many authors investigate robustness of optical 3D scanners encountering translucent objects, but few consider the bias problem, which affects the accuracy of the scans. To counteract the bias problem, Inoshita *et al.* [22] use a single scattering model to estimate both scattering properties and object shape. While their technique shows some potential, its accuracy suffers from low intensity of the singly scattered light.

In work by Godin *et al.* [23], a laser based 3D scanning system is used for digitizing marble sculptures. Marble's translucency and heterogeneous structure produce significant bias and increased noise in dimensional measurements. A bias was indeed observed, but, because of the strong surface reflection compared to the subsurface scattering, its impact is shown to be limited.

Wilm *et al.* [24] investigate on the accuracy of a structured light scanner using the same step gauges considered in the present work. This is accompanied by a dimensional verification and an uncertainty assessment. Results put in evidence a great influence of the material and the colours of the step gauges, but the experiments were limited to a single 3D optical scanner. Generally, when dealing with the subsurface scattering effect, one would consider active optically based systems [25]. Even so, the influence of the object material and colours is also of great importance for passive optical scanners, such as ones exploiting the photogrammetric principle. This is the case, since the success of the reconstruction is strictly connected to the visible surface texture, which determines the number of common features recognized among multi-view images of the object [26]. In previous work [4], a photogrammetric system is used for the measurement of microfluidic devices realized by additive manufacturing of polymers. Here, many criticalities arose due to the smoothness of those materials.

In this work, using the step gauges also used by Wilm *et al.* [24], the analysis is extended to other 3D optical scanners exploiting different measuring principles, in order to understand and quantify the interaction between the optical properties of each material with the measuring system adopted, in terms of measurement error and quality of reconstruction.

The paper is structured with a section dedicated to the Materials and Methods, describing the reference object, the measuring equipment, the measuring procedure and the method for the uncertainty assessment. Then, results will be reported in the dedicated section, followed by their discussion.

3. Materials and methods

In the following sections, a description of the miniature step gauge, the measuring equipment used and the measuring procedure are reported, together with a description of the method for the uncertainty assessment.

3.1 Step gauges description

The step gauge was firstly adopted in [27] for the optical scanning of small parts, and it was fabricated with a bisacryl material. Afterwards, step gauges were used for the performance verification and systematic error correction of CT scanning systems. Different materials were used for the fabrication and mostly polymers due to their low density, which makes them suitable for CT scanning. According to [28] the polymers used, Peek and PPS with 40% of glass, resulted in step gauges fulfilling the needs for stability over time and surface quality. In this work, five step gauges having the same nominal dimensions, 58x7x8 mm³, but made of different polymers and colours [24], see *Table 1*, were scanned and measured using 3D optical scanners exploiting different measuring principles.

Table 1 List of the step gauges used in this work: materials and colours.

Step gauge	Material	Colour	Coefficient of Thermal Expansion [10 ⁻⁶ *K ⁻¹]
POM-C#1	Polyoxymethylene (POM)	Colourless	120
ABS-G#1	Acrylonitrile butadiene styrene (ABS)	Grey	90
PPS-B#7	Polyphenylene sulfide (PPS)	Black	30
POM-B#1	Polyoxymethylene (POM)	Blue	90
PK-B#1	Polyether ether ketone (PEEK)	Beige	50

The step gauge geometry features unidirectional and bidirectional lengths. Their graphical definition is shown in *Figure 1*. The following equations serve to explain the effect of shifting the measuring point from the real surface towards the inside. Note that it is not possible to detect this effect with the unidirectional lengths (L_{Um} , L_{Uc}), but it becomes possible with the bidirectional lengths (L_{Bm} , L_{Bc}), where the “offset”, expressed as Δl in the equations, is added to the result twice.

Figure 1 Step gauge unidirectional and bidirectional lengths definition.

$$L_{Um} = w_g + w_t - \Delta l + \Delta l \quad (1.1)$$

$$L_{Bm} = w_g + w_t + w_g + \Delta l + \Delta l, \quad (1.2)$$

where

L_{Bm} is the measured bidirectional length;

L_{Bc} is the calibrated bidirectional length with a contact probe;

L_{Um} is the measured unidirectional length;

L_{Uc} is the calibrated unidirectional length with a contact probe;

w_g is the groove width;

w_t is the tooth width;

Δl is the offset respect to the real surface of the object;

In this work, the lengths reported in *Figure 2*, were considered as measurands.

Figure 2 Unidirectional and bidirectional lengths considered. Measures are expressed in mm.

3.2 3D scanners used in this investigation

The five step gauges were scanned with different optical instruments. A laser line scanner, two commercial structured light scanners, a structured light scanner realized at the Department of Applied Mathematics and Computer Science of the Technical University of Denmark and, finally, a photogrammetric scanner realized at the Department of Mechanics, Mathematics and Management of Polytechnic University of Bari. Both structured light scanners and the laser line scanner are counted among active optical systems, since a sinusoidal pattern or a laser strip is projected onto the object surface and then acquired, while, the photogrammetric system adopted is a passive system, without the projection of any pattern. The scanners are listed below and the scanning strategy reported for each case.

- 3SHAPE D800, a laser line scanner with a red beam ($\lambda=630-680$ nm) with a resolution of 0.02 mm. The scanner movements are computed by a tilting and rotating table, which allow the exploitation of different scanning strategies to scan complex and freeform parts. The scanning strategy adopted in this case was a tilt angle of 45° and a rotary stage of 36° , which means 10 acquisitions. This scanner is recognized in the paper as **LLS**. *Convince* software was used for the data processing and the meshing operation.
- GOM ATOS III scan Rev. 2, equipped with 90 mm lenses, which allow measurement of a working volume of $60 \times 45 \times 30$ mm³ with a resolution of 0.017 mm. This is a structured light scanner with blue light, in order to avoid the influence of the environmental illumination. The scanning strategy adopted was a polar scan, with the step gauge positioned at the centre of rotary table and 8 acquisitions were carried out every 45° , while the sensor was tilted 45° with respect to the rotary table (xy plane). This scanner is recognized in the paper as **SLS-1**. *GOM Inspect* software was used for point cloud processing and the meshing process.
- ATOS Capsule, an optical precision measuring machine (OPMM) for full-field digitizing of contoured part geometries. The system exploits the triple scan technology, with two cameras

and the projection unit: precise fringe patterns are projected onto the surface of the object and are recorded by two cameras, based on the stereo camera principle. The system used in this work is a 12MP sensor with a measurement area of 120mm x 80mm, with a resolution of 0.027 mm. The acquisitions were performed firstly with the sensor tilted at 90° and then with the sensor tilted of 60° while the turning table was rotated every 45°, which means 8 acquisitions. This scanner will be indicated in the next sections as **SLS-2**. *GOM Inspect* software was used for point cloud processing and the meshing process.

- The structured light scanner from DTU compute is set up according to Figure 3. It consists of two industrial cameras (Point Grey GS3-U3-91S6C-C, 9MPx) with 54 mm lenses and a field of view of approximately 250x150x150 mm. It is also equipped with a pattern projector (LG PF1500, 1920x1080) and rotation stage (Newmark Systems RM- 5). It is equipped with a “white light” home cinema projector as light source. The two-frequency heterodyne principle was used for phase shift encoding with 40/41 fringe periods and 16/8 primary and secondary steps. Additionally, we also used a 8-step Gray code pattern including its binary inverse. A precision study has previously been performed on the scanner, see [29] for more technical details. Using the same method presented in [24], the step gauges were placed in a custom 3D printed fixture and scanned from 16 different angles. Alignment was based on a calibrated rotation axis fine-tuned using optical markers with an iterative marker-estimation algorithm. Reconstruction was done using Meshlab. These will be indicated in the next sections as **SLS-PS** and **SLS-GC**, according to the used approach: phase shift or gray code, respectively.
- **PSSRT**, a Photogrammetric Scanning System with Rotary Table, equipped with a Canon Eos 760D, a Canon EF 50 mm 1:1.8 II objective lens and an extension tube of 20 mm, which determines a consequent ground resolution of 0.012 mm/pixel. The sensor was tilted of 45° and 72 pictures were taken rotating the object with a step of 5°. The optimal light conditions were assured by using three led lamps, one placed at the top of the object and two placed behind the camera and inclined at the same tilt angle. The system shows characteristics comparable with the commercially available 3D optical scanners [30]. In this case, the adjustment of the scaling process was carried out through the calibrated unidirectional lengths. The reconstruction was carried out with Agisoft Photoscan v. 1.2.6.

Figure 3 Structured light scanner from DTU Compute.

The step gauges were scanned five times for each instrument involved in the analysis. The acquired surfaces, in the form of polygonised meshes, were analysed with the GOM inspect software, and the distances between the groove sides were computed as distances between corresponding points on each groove side. Before computing the resulting errors, temperature compensation must be done for the LLS, the SLS-GC and the SLS-PS. Indeed, temperatures registered was 23.5° for the LLS and 23.75 for the

SLS-GC and SLS-PS. Humidity was also registered and it was ranging within 48-50% for the SLS, while it was not detectable for the other scanners, thus, a humidity compensation was not carried out in this investigation.

3.3 Uncertainty assessment

The uncertainty evaluation was conducted according to the ISO 14253-2 [31], as a simplification of the GUM approach [32].

The general equation is reported (Eq. 1.3) and the confidence level is set to 95% to which corresponds a coverage factor $k = 2$.

$$U = k \sqrt{u_r^2 + u_w^2 + u_e^2 + u_p^2}. \quad (1.3)$$

The uncertainty contributors are reported in *Table 2*. Starting from that, the uncertainty of calibration was considered as the uncertainty of calibration of each measurand (step gauge unidirectional and bidirectional lengths). The uncertainty component related to the instrument was not considered due to the difficult estimation of the MPE (Maximum Permissible Error) for the optical scanners considered. This is the case, since it is strongly dependent on the visible texture characteristics coming from the combination between materials and colours, while other approaches, e.g. considering the optical resolution, would have led to a high overestimation of the uncertainty. The uncertainty coming from the workpiece was considered as the standard deviation of the fitting error, which is the variability of the normal distances between each point on the real surface and the corresponding one on the fitted plane. The component due to the environmental temperature was also considered, and, finally, the uncertainty due to the measuring repeatability was evaluated as standard deviation of the mean of five repetitions.

Table 2 Uncertainty budget composition.

Uncertainty component	Symbol	Type	Estimation	Distrib.	LLS	SLS-1	SLS-2	SLS-GC/PS	PPSRT
Reference	u_r	B	Reference Uncertainty	Rect.	$U_i/\sqrt{3}$	$U_i/\sqrt{3}$	$U_i/\sqrt{3}$	$U_i/\sqrt{3}$	$U_i/\sqrt{3}$
Workpiece	u_w	A	Form error	Rect.	σ fitting error	σ fitting error	σ fitting error	σ fitting error	σ fitting error
Environment	u_e	B	Temperature variation	U-shaped	$\pm 1.5^\circ \text{C}$	$\pm 1^\circ \text{C}$	$\pm 1^\circ \text{C}$	$\pm 1.25^\circ \text{C}$	$\pm 1^\circ \text{C}$
Repeatability	u_p	A	Repeated measurements	Normal	$\sigma_{LLS}\sqrt{n}$	$\sigma_{SLS-1}/\sqrt{n}$	$\sigma_{SLS-2}/\sqrt{n}$	$\sigma_{SLS}\sqrt{n}$	$\sigma_{PPSRT}\sqrt{n}$

4. Results

Before reporting the overall numerical results, a summary of results is shown in *Table 3*. Results are divided into two categories: *cooperative* and *not cooperative*. Cooperative means that the point cloud acquisition produced analysable results, and, in that case, an indication of the errors registered was reported, while the not cooperative means that the measurement was not successful because of few points acquired on the sample surface, which made the reconstructed surfaces not analysable. In that case, in the table the text “No data” is reported.

Errors reported in *Table 3* are defined as the maximum values of error registered for each combination scanner-object, considering the unidirectional lengths.

Table 3 First summary of results of the step gauges acquisition. Errors reported are the maximum values of error, considering, for each case, the unidirectional lengths.

	LLS	SLS-1	SLS-2	SLS-GC	SLS-PS	PSSRT
POM-C#1	No data	No data	No data	No data	0.03 mm	No data
ABS-G#1	0.005 mm	0.002 mm	0.015 mm	0.05 mm	0.005 mm	No data
PPS-B#7	0.003 mm	0.001 mm	0.001 mm	0.03 mm	0.015 mm	0.002 mm
POM-B#1	0.03 mm	No data	No data	0.04 mm	0.01 mm	No data
PK-B#1	0.008 mm	0.005 mm	0.004 mm	0.035 mm	0.005 mm	No data

4.1 Dimensional verification of the step gauge

Firstly, unidirectional lengths were computed for each step gauge and each optical instrument that produced analysable results. The output variable chosen was the error evaluated with respect to the CMM calibrated values, following

$$Error = \overline{X_{ij}} - \overline{X_{cal}}, \quad (1.4)$$

where,

$\overline{X_{ij}}$ is the average value (five repetitions) of the analysed length belonging to the i^{th} step gauge, measured with the j^{th} optical scanner and compared with $\overline{X_{cal}}$, the calibrated value for that length.

Considering the step gauge made of ABS, see *Figure 4*, the errors were comprised between -0.05 mm and 0.01 mm for all the scanners involved. However, if only the LLS, SLS-1/2 are considered, errors registered were within ± 0.005 mm, highlighting a good agreement among them. Uncertainties were assessed to be below 0.03 mm.

Figure 4 Errors on unidirectional lengths for the step gauge ABS-G#1.

Figure 5 Errors on unidirectional lengths for the step gauge PPS-B#7.

Same considerations could be done for the PPS-B#7 step gauge, see Figure 5, where the group composed by LLS SLS-1/2 and SLS-PS showed errors comprised between ± 0.02 . The SLS-GC showed instead errors

up to -0.04 mm. Uncertainties were less than 0.01mm for most of the scanners and 0.05 mm for SLS-GC and 0.06 for SLS-PS.

The PK-B#1, see *Figure 6*, registered errors comprised between ± 0.005 mm for LLS, SLS-1/2 and errors within 0.02 and -0.04 mm for the SLS-PS and SLS-GC. Uncertainties were about 0.005 mm for the SLS-1, 0.01 mm for LLS and SLS-2, and less than 0.02 mm for the rest of the scanners.

Figure 6 Errors on unidirectional lengths for the step gauge PK-B#1.

The step gauge made of blue POM, see *Figure 7*, was acquired only by three scanners: the LLS, the SLS-PS and SLS-GC. Errors registered for the LLS were the highest registered for this scanner and they were up to -0.03 mm. The SLS-PS and SLS-GC showed similar results. A relevant difference as compared with the other cases was found in the uncertainty. This was on the order of 0.05 mm for the SLS-PS and 0.04 for SLS-GC, while it was about 0.02 mm for the LLS. Finally, the step gauge made of colourless POM was analysed, it is reported in *Figure 7*, together with the blue POM. It was successfully acquired only by the SLS-PS, with errors and uncertainties comparable with the ones obtained for the POM-B#1.

Figure 7 Errors on unidirectional lengths for the step gauges made of POM. The letter B, after the scanner name indicates the POM-B#1 step gauge, while the letter C indicates the POM-C#1.

The general observation is that, regarding the unidirectional lengths, there are no relevant differences between the scanners involved in the investigation and, even in the case of SLS-GC and SLS-PS they were comprised in a narrow range. More important for the current investigation are the errors evaluated on bidirectional lengths, as explained in the introduction. As expected, errors evaluated on bidirectional lengths were higher than errors evaluated on unidirectional lengths.

Figure 8 Errors on bidirectional lengths obtained for the ABS-G#1 step gauge.

Considering the ABS-G#1, see *Figure 8*, the average error computed was on the order of 0.02 mm for the SLS-1, 0.01 mm for the SLS-2, while the average error computed for the LLS was about 0.03 mm. Definitely higher were errors registered for the SLS-GC and SLS-PS, on the order of 0.2 mm, with a worse performance for the SLS-PS. The uncertainties were below 0.01 mm for the SLS-1, SLS-2 and LLS, while they were doubled in the case of SLS-GC and SLS-PS.

The PPS-B#7, see *Figure 9*, was characterized by a similar “offset” between the different instruments involved. In particular, errors registered for the SLS-1 were in the same order of the errors obtained for the unidirectional lengths, while the LLS presented errors in the order of 0.01 mm. The PSSRT and the SLS-2 showed a similar trend but with errors which have opposite sign with respect to the other scanners and they were about -0.01 mm. Finally, SLS-GC and SLS-PS showed errors in the order of 0.5 mm and 0.6 mm, respectively. Uncertainties were less than 0.01 mm for the LLS, SLS-1, SLS-2 and PSSRT, while they were about 0.05 and 0.06 mm for SLS-GC and SLS-PS, respectively.

Figure 9 Errors on bidirectional lengths obtained for the PPS-B#7 step gauge.

The PK-B#1 was characterized by better defined offsets, see *Figure 10*. In particular, SLS-2 showed the lowest errors, about 0.02 mm, less than the error registered for SLS-1 and a half of the error registered for the LLS (0.045 mm). SLS-GC and SLS-PS registered errors on the order of 0.3 mm and 0.4 mm. Uncertainties were about 0.01 mm for LLS, SLS-1 and SLS-2, while they were about 0.02 mm for the SLS-GC and SLS-PS.

Figure 10 Errors on bidirectional lengths obtained for the PK-B#1 step gauge.

Finally the two step gauges made of POM were measured and analysed, see Figure 11. The POM-B#1 was successfully scanned by the LLS and the SLS-GC and SLS-PS. The LLS registered errors on the order of 0.05 mm, SLS-GC, 0.45 mm and SLS-PS, 0.65 mm. Uncertainties for the two, SLS-GC and SLS-PS, were up to 0.06 mm. Moreover, SLS-PS was the only scanner to produce analysable data of POM-C#1, which was the worst combination material and colour among the five step gauges, with errors up to 0.8 mm and uncertainties of 0.08 mm.

Figure 11 Errors on bidirectional lengths obtained for the POM step gauges. The letter B, after the scanner name, indicates the POM-B#1 step gauge, while the letter C indicates the POM-C#1.

4.2 Quality of reconstruction: Flatness analysis

Besides the dimensional verification, flatness registered on the acquired surfaces was considered, in order to take into account the other effect due to the material translucency, which is a different surface quality retrieved, other than a simple bias. This effect leads to an increase of the uncertainty for the cases where a poor reconstruction quality is obtained. A way to evaluate the quality of the reconstruction and, eventually, the differences due to the materials and colours, is the evaluation of the flatness of each groove side, the left groove side and the right groove side, see *Figure 12*.

Figure 12 Indication of left and right side of each groove.

The flatness was retrieved with the *GOM Inspect* software. As it is possible to observe, the flatness values were different according to the instrument used and the material considered. They were about 0.05 mm for all the scanners involved when used for measuring ABS and PEEK, see *Figure 13* and *Figure 15*, while PPS resulted to be a difficult combination material-colour for the SLS-PS and SLS-GC, see *Figure 14*, as well as the POM in both its colours, see *Figure 16*. For the latter, the flatness values were up to 0.15 mm. The analysis showed that the best performance is attributable to the SLS-1/2 with flatness values on the order of 0.01 mm. Those results are quite in agreement with the dimensional accuracy results.

Figure 13 Flatness evaluated on the ABS-G#1 for each instrument involved.

Figure 14 Flatness evaluated on the PPS-B#7 for each instrument involved.

Figure 15 Flatness evaluated on the PK-B#1 for each instrument involved.

Figure 16 Flatness evaluated on the POM step gauges for each instrument involved. The letter B, after the scanner name, indicates the POM-B#1 step gauge, while the letter C indicates the POM-C#1.

5. Discussion of results

The presented measurements are noticeably affected by the interactions between the optical instruments and the material properties of each step gauge. In fact, it is not possible to attribute the significant difference between measured bidirectional lengths to inaccuracies, as all the instruments involved showed similar accuracies, assessed through the unidirectional lengths. The unidirectional errors were found within ± 0.005 mm for the LLS, SLS-1, SLS-2 and PSSRT, and within -0.05 mm and 0.01 mm for the SLS-GC and SLS-PS. In comparison, the bidirectional errors were found between -0.01 mm and 0.8 mm, depending on the instrument and the step gauge. There are, indeed, significant differences observed between the optical instruments. Some of them, like the SLS-1/2, are only weakly affected, while others like the SLS-GC/PS are much more strongly affected. To facilitate further analysis and discussion, we introduce the optical penetration depth,

$$\varepsilon_{ij} = \frac{Error_{ij}}{2}, \quad (1.5)$$

where ε_{ij} is the penetration depth computed for the i^{th} step gauge with the j^{th} optical scanner. The $Error_{ij}$ is the average bidirectional error estimated according to Eq. (1.4) considering the error of each measurand, covering the step gauge length. Moreover, an uncertainty was associated to each value and it was evaluated as the standard deviation of the above mentioned bidirectional length errors.

Figure 17 Optical penetration depth for each combination material-scanner.

Looking at Figure 17, the PPS-B#7 produced the smallest subsurface scattering effect for the LLS, SLS-1, SLS-2 and PSSRT, with values comparable with the errors evaluated on unidirectional lengths. The behaviour is different for the SLS-PS and SLS-GC. Over all, the ABS-G#1 step gauge displays the smallest values of subsurface scattering for all the scanners involved and only in the case of SLS-GC and SLS-PS it reached the 0.2 mm. The PK-B#1 registered a more pronounced effect for all the scanners, while the POM-B and POM-C were the worst materials to scan.

On the instrument side, the SLS-GC and SLS-PS were affected the most by the translucency of the materials involved. One possible explanation is the light source, which is different from the others. The scanner SLS-GC/PS uses a red, green and blue (white) light source and, in terms of subsurface scattering, each of the wave lengths must undergo different levels of scattering resulting in chromatic aberrations. As opposed to this, the GOM ATOS scanners (SLS-1/2) use a blue light source, which has been reported to reduce the effects of subsurface scattering [33]. In addition, their method of phase-shifting is applied (sequentially) in two orthogonal directions. In a sense, this could be considered a sequential version of modulated phase-shifting [17]. The LLS scanner uses a different source entirely, namely a red beam laser line. We have found no previous studies reporting advantages of using a red laser beam. However, it is possible to use the intensity differences in the beam shape to get a fairly accurate estimate of the laser entry point [8]. Furthermore, a laser may experience problems due to speckle in the presence of subsurface scattering. The wide bandwidth of the LLS laser is likely to reduce said speckle effects, and use of the beam shape may be the reason why this scanner performs better than SLS-GC and SLS-PS. The improved accuracy of SLS-1/2 as compared with LLS is then likely due to the blue light used in the SLS-1/2. The PSSRT scanner, which considers only the PPS-B#7 step gauge, showed an offset of opposite sign compared with the others. This means that the optical effect in this case seems to be the opposite of the light penetration. In fact, the photogrammetric system used in this case exploits the photogrammetric principle and is a passive system, without the projection of any pattern or a laser beam. As such, it relies on diffuse illumination i.e. light from several directions. The light paths in case of subsurface scattering are then much more intricate than for the other scanners. To fully understand the differences observed in this study, further investigations will have to be carried out considering photogrammetric systems equipped as active systems. We note that the same effect was found for the SLS-2. Both of the SLS1-1/2 and the LLS are commercial systems that may or may not apply a plethora of (unknown) post-processing steps to the measured data, many of which could indeed explain the origin of this negative offset.

Finally, the flatness was also analysed as an index of the quality of reconstruction. Similar to the errors (see Eq. 1.5), the average flatness of all grooves for each step gauges is considered, see *Figure 18*. Generally, results are quite in agreement with the ones regarding the dimensional errors. The most critical material was the POM-B and POM-C. The best materials were the ABS and PEEK, while the PPS severely affected the SLS-GC and SLS-PS measurements, in agreement with the dimensional verification. This behaviour is different from all other scanners involved, and can be explained by the black colour of the material. Black objects are challenging for optical scanners by their very nature of reflecting very little light. This means that factors such as camera quality become more important, and different systems are affected differently. The SLS-GC/PS scanner may very well be less suited for black objects than the others. The lowest registered values of form error were found for the SLS-1 and SLS-2 scanners. Considering all the step gauges they were on the order of 0.02 mm. The quality of reconstruction i.e. the flatness was also included in the uncertainty budgets. The dual effect of the translucency of materials is thus accounted for in both measurement of the dimensional errors (the bias), and the computation of uncertainties of the same dimensional errors.

Figure 18 Flatness values for each combination material-scanner.

6. Conclusion

In this work, five step gauges made of different materials and colours were scanned and measured with different 3D optical scanners, with the aim to investigate their optical interactions. The dimensional analysis highlighted that the translucent polymer materials have a significant effect on the dimensional verification and its amount depends on the instrument involved. The best behaviour was registered for the SLS-1 and SLS-2, which were the commercial structured light scanners, while the most marked effects due to the translucency of the materials analysed were registered for the SLS-GC and SLS-PS. The LLS was slightly more sensitive to the subsurface scattering and the PSSRT, which was a passive system, registered a small error below 0.01 mm with the opposite sign respect to the other instruments. It is important to note, however, that results obtained for the PSSRT refer to only one step gauge, the one made of PPS, and a further investigation is required for the analysis using the PSSRT as an active system. The homebuilt structured light scanner (SLS-GC/PS) displays significantly higher subsurface scattering effect, if compared to the commercial scanners. It was, however, the only scanner able to scan all the supplied translucent objects.

One reason the DTU scanner outperforms the commercial ones (in terms of widest acceptable range of step gauge material) might simply be a low noise tolerance built in to the commercial scanner's software. The DTU scanner is allowed to operate on arbitrarily high tolerances, which are tailored for the experiments in question. While this is also likely to contribute to the relatively large errors observed for the DTU scanner, it does allow it to operate on materials that the other scanner simply cannot. Poor results are sometimes better than no results, and the SLS-GC/PS might be one way towards understanding the influence of subsurface scattering in optical 3D scanning. However, the obtained results suggest problems that need to be addressed before taking steps toward developing new (e.g. bias compensation) techniques for scanning translucent materials. For one, the light source plays an important role, which, upon further studies, should be considered.

Finally, a quality analysis of the reconstruction was conducted by considering the flatness of each groove side, showing results in good agreement with the dimensional verification. Moreover, the fitting error was considered in the uncertainty budget and this allowed us to observe the dual effect of the optical interaction between the 3D scanner and the translucent materials: the measurement bias and the increased uncertainty.

In conclusion, the subsurface scattering effect is relevant and should be considered when the dimensional verification of polymers has to be carried out. This work represents a first step towards a subsequent *bias compensation*. The further idea could be to embed the compensation of the bias produced by the optical interactions between the scanner and measured materials in the measuring procedure. To this end, further experiments and studies are needed and more instruments and more materials and colours of interest for the manufacturing field, has to be involved in the analysis.

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