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Effects of subsurface scattering on the accuracy of optical 3D measurements using miniature polymer step gauges

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We present a study on the effects of sub-surface scattering quantified by means of uni- and bidirectional distance measurements on miniature step gauges, which were manufactured in four different polymer materials (POM, PEEK, PPS and ABS), and calibrated using a coordinate measuring machine. Measurement were performed using an own developed structured light 3D scanner, which provides detailed knowledge of the scan process and allows access to raw data and unbiased evaluation of the sub-surface effects. Analysis was carried out with the CMM measurement strategy adapted to optical data in the software GOM Inspect.
Results show bidirectional deviations (optical measurement compared to CMM) in the order of 100µm to 800µm (material dependent) and consistently higher than corresponding unidirectional measurements, indicating a systematic error induced by the light-material interaction. We hypothesize that part of these effects can be accounted for, enabling optical measurements of a wider range of materials.

Optical metrology, 3D scanning, Dimensional Accuracy, Polymers

1. Introduction

Optical 3D scanning is quickly being adopted for a range of measurement tasks due to its fast, dense and contactless nature. Its application is usually limited to metallic items, which reflect light strictly at the air/material interface, where high accuracy can then be achieved (length measurement uncertainty down to 1µm). Polymers and ceramics play a big role in precision manufacturing, but exhibit varying degrees of translucency, in which case some light penetrates the object and is scattered sub-surface. This will offset the triangulated point-measurements towards the inside of the object. Hence, optical 3D scanning is usually not considered applicable for polymers.

The interactions of light and material are highly complex and difficult to model in general. State of the art within computer graphics use e.g. BSSRDF (bidirectional scattering-surface reflectance distribution function) models and suitable approximations. In the context of this study, we consider the material to be texture less, homogenous and semi-infinite. In that case, we can characterize the individual samples by means of wavelength-varying absorption and sub-surface scattering coefficients (commonly denoted μ_a and μ_s). Fringe projection (or generally structured light) 3D scan systems rely on the principle of image correspondence finding and triangulation. While the machine vision community acknowledges the fact that sub-surface effects offset features locations, and hence affect measurement accuracy, it is not possible to entirely correct for them without detailed knowledge and modelling of the material optical properties. The choice of spatially encoding structured light patterns does however influence how sensitive the process is to sub-surface reflection [1]. Most mitigation strategies rely on the separation of reflected light into its direct and global components [2—3].

This study quantifies the sub-surface effect using metrology accepted standards on five step-gauges of four different polymer materials, all of different colour and exhibiting different amounts of translucency (μ_a and μ_s profiles) as illustrated in Figure 1. Here it is also illustrated how the different samples diffuse the high frequency checkerboard pattern to different degrees due to sub-surface effects. We utilize an own developed structured light 3D platform, which gives us full insight and control over the acquisition process and provides us with the raw triangulated point coordinates.

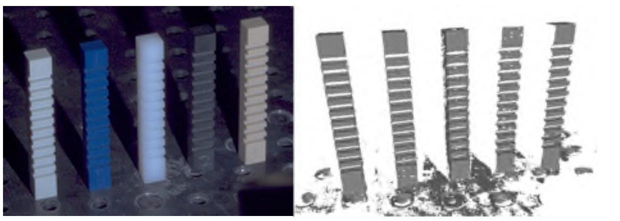

Figure 1. Left: tone mapped high dynamic range (HDR) image of step gauges with high frequency checkerboard pattern. Right: corresponding shaded 3D point cloud. From left to right: ABS, POM-Blue, POM-Colorless, PPS, PEEK.

We have validated our scanner and calibration procedure by means of VDI2634 part 2[4] and demonstrated geometric accuracy similar to a commercial and metrology accepted system (GOM Atos III) [5]. This data is considered useful both as a general indication of the measurement error incurred in polymer material and as a comparison of the error between different polymers and colours.

2. Methods

The five miniature step gauges shown in Figure 1 were measured in using a CMM (Zeiss OMC 850) according to the measurement strategy detailed in Sec. 2.3. Optical measurements were performed on the same samples as explained below.

2.1. Miniature step gauges

The geometry of our step gauges is shown in Figure 2.

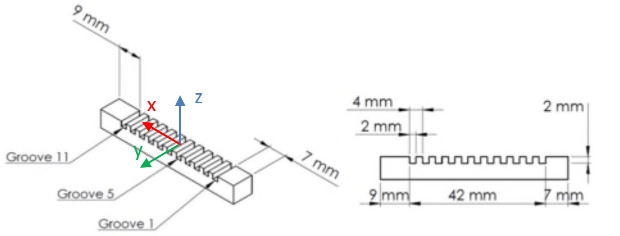

Figure 2. Nominal geometry of our step gauges. A reference system is defined on the near upper edge of groove 6 with x red, y green, z blue.

Two classes of measurands are defined; unidirectional distances between grooves $M_{\mathrm{U}x},\ x \in [1;10]$ and bidirectional distances $M_{\mathrm{B}y},\ y \in [1;10]$. These are defined on the reference system shown in Figure 2 as distances between planes x=x1 and x=x2. The individual measurands are defined in Table 1.

2.2. Optical 3D measurements

The optical 3D scanner consists of two industrial cameras (Point Grey GS3-U3-91S6C-C, 9MPx), a pattern projector (LG PF1500, 1920x1080) and rotation stage (Newmark Systems RM-5) with a field of view of approximately 250x150x150 mm. The two-frequency heterodyne principle was used for spatial encoding with 40/41 fringe periods and 16 primary steps. A pixel-based high dynamic range (HDR) sequence was used for POX-C and PPS due to the large dynamic range in those scenes.

Camera calibration was based on Zhang's method with 34 stereo observations of a checkerboard containing 228 saddle points and a second order polynomial radial distortion model.

The step gauges were scanned in a custom 3D printed fixture with 14 part-scans each. Initial alignment was based on the calibrated rotation axis and fine-alignment on 14 circular optical markers with an iterative marker-estimation algorithm based on projection to stereo-pairs and a final bundle-adjustment step.

All measurements were conducted in a non-temperature controlled environment at temperatures in the range [22.5 – 23.1 °C].

2.3. Measurement strategy

The strategy for CMM reference measurements was based on 3-2-1 alignment with the x-y plane fitted to the central four teeth of the step gauges, the x-direction by means of least squares fitting to the sides of the gauges and the y-direction by fitting to the side wall of the sixths groove.

For the optical point cloud data, the same measurement strategy was implemented in GOM Inspect Professional.

3. Results

Table 1 shows the definitions of the measurands and the determined deviation to the CMM calibrated distance.

Table 1: Results of M*x* (optical) – M*x* (CMM) and their uncertainties.

Meas.	(x1; x2) [mm]	Dev. to CMM. [µm]				
		ABS	POM-B	POM-C	PPS	PEEK
$M_{\mathrm{U}1}$	(0; 4)	-2	101	-1	7	-1
$M_{\mathrm{U}2}$	(0; 8)	1	-27	-24	-51	-3
M_{U3}	(0; 12)	-12	45	-37	-93	-20
$M_{\mathrm{U}4}$	(0; 16)	-15	-5	20	6	-9
$M_{\mathrm{U}5}$	(0; 20)	-21	-21	13	-51	-16
$M_{\mathrm{U}6}$	(0; -4)	-13	-42	26	-12	-12
$M_{\mathrm{U}7}$	(0; -8)	-26	-63	-57	-12	-29
$M_{\mathrm{U}8}$	(0; -12)	-28	-126	52	-71	-19
$M_{\mathrm{U}9}$	(0; -16)	-37	-101	60	-38	-31
$M_{\mathrm{U}10}$	(0; -20)	-35	-110	-91	-82	-43
U_{U}		±13	±71	±48	±36	±13
$M_{\mathrm{B}1}$	(0; 2)	75	493	743	303	145
$M_{\mathrm{B}2}$	(0; 6)	100	487	770	267	139
$M_{\mathrm{B}3}$	(0; 10)	97	427	823	196	140
$M_{\mathrm{B}4}$	(0; 14)	101	440	782	222	131
$M_{\mathrm{B}5}$	(0; 18)	77	457	785	218	129
$M_{\mathrm{B}6}$	(0; 22)	79	407	778	183	118
$M_{\mathrm{B}7}$	(0; -2)	-120	-517	-827	-286	-170
$M_{\mathrm{B}8}$	(0; -6)	-126	-457	-824	-321	-165
$M_{\mathrm{B}9}$	(0; -10)	-124	-503	-800	-258	-177
$M_{\mathrm{B}10}$	(0; -14)	-121	-475	-776	-288	-186
U_{B}		±20	±35	±27	±47	±23

CMM expanded measurement uncertainty was evaluated based on machine specifications, workpiece form error, temperature effects and reproducibility (5 repetitions), and did not exceed 7.7µm for any measurand (safety factor: 2.0). The uncertainties of optical scan deviations, denoted U_{U} and U_{B} were estimated as the standard deviation of values (absolute values for bidirectional measurands).

4. Conclusions

The results show consistently unbiased deviations for unidirectional and deviations for bidirectional measurements that show that the surface is indeed offset toward the sample inner (positive deviations in M_{B1-6} and negative deviations in M_{B7-10}). This demonstrates that the absolute measurements (unidirectional) are very close to the reference, while sub-surface effect offset the measured surface into the material.

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