INNOVATIVE MECHANICAL ENGINEERINGISSN **2812-9229 (Online)**
University of Niš, Faculty of Mechanical Engineering
VOL. 2, NO 2, 2023, PP. 76 -87

Original scientific paper *

THE INFLUENCE OF AN OBJECT'S COLOR AND TOPOLOGY ON THE PRECISION OF THE 3D SCANNING PROCESS AND THE QUALITY OF THE OBTAINED CAD MODEL

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Abstract. *3D scanning technologies are potential tools for increasing productivity, accuracy, and ensuring high product quality. Laser triangulation-based 3D scanning has a wide range of applications in quality control, measurement, and reverse engineering, thereby making processes more efficient. The major advantage of this technology lies in its resolution and precision. However, it is highly sensitive to the surface and color of an object. This study presents the influence of surface and color of an object on the quality of the 3D scan model. The objects of scanning were coated with glossy and matte lacquer. The Range Vision Smart 3D scanner was used, which provided a scan in the form of a stereolithographic file, using the corresponding ScanCenter NG 2022.1 software*.

Key words:*3D scanning, CAD model, 3D printing*

1. INTRODUCTION

3D scanning is a novel computer aided (CA) technique suitable for the fast creation of CAD models. And that is today's main goal: to be fast and precise. The technique is based on lighting, illumination and laser triangulation. As such, it has found its wide application in product development and reverse engineering.

The process of 3D product modeling is an extremely time/money consuming process even with advanced CA technologies. In the case of reparation or reverse engineering, where the main object exists, the use of 3D scanners is highly significant since it can help in generating high-resolution CAD models [1].

However, this feature/technique is not always straightforward when it comes to creating a useful CAD model. The state-of-the-art 3D scanning systems still have significant issues

*Received: July 16, 2023 / Accepted October 24, 2023.**
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with color, texture and topology of the object of interest, which in most of the cases results in imprecise and non consistent CAD models that require further repairs – more time and money [2]. Therefore, it is important to recognize where the "bottle necks" are while working with 3D scanning.

Lemeš *et al.* [3] demonstrated the relationship between ambient light intensity, color of the scanned surface, and the quality of laser scanning. After conducting their research, they concluded that the best scanning results were achieved when the object's surface had a light-absorbing property. However, there was a particularly strong influence of the lights when scanning glossy white, yellow, and green surfaces [3].

The influence of certain color characteristics in laboratory conditions and the application of the Cyrax 2500 scanner were demonstrated by J. Clark and S. Robson [4] in their work, in which they investigated a high correlation between the quality measures of the point data returned by the scanner. The significant differences were found when the planar color chart was rotated at angles up to 60° with respect to the scanner. At 60° angles, the point data density began to noticeably decrease, making angles of 40° more practical. The results aligned with the expectation that colors with low reflectance at 532nm, such as black and red, reflect rays to a lesser extent [4].

This paper will discuss the use of modern software tools in product development. An object of interest was a complex object (from the aspects of surface and shape), primarily modeled in CA software. Afterwards this model was printed and colored, and finally, scanned for the creation of a CAD model. This model was compared with the initial CAD model with a goal to estimate the error of the CAD-print-scan-CAD procedure. The CAD tool was SolidWorks and and a Creality CR-6 SE 3D printer was used. Subsequently, the product control procedure was applied using the RangeVision Smart 3D scanner. This will showcase the analysis of product control with different surface structures. These analyses contribute to significant savings in the product development process and reverse engineering, as the greatest savings are achieved during the design and engineering phases. During product control [5, 6], using a 3D scanner, many factors influence the accuracy of the results, including factors that alter the reflected laser image captured by the cameras, potentially introducing errors. Besides surface geometry, surface parameters such as material, color, and finishing also affect reflection, greatly impacting different surfaces.

The aim of this paper is to provide a comparison between a 3D virtual model and scanned blue and red models, made of the same material. Additionally, it aims to examine the deviation between the 3D virtual model and scanned red and blue models that were coated with glossy pink paint and a matte finish.

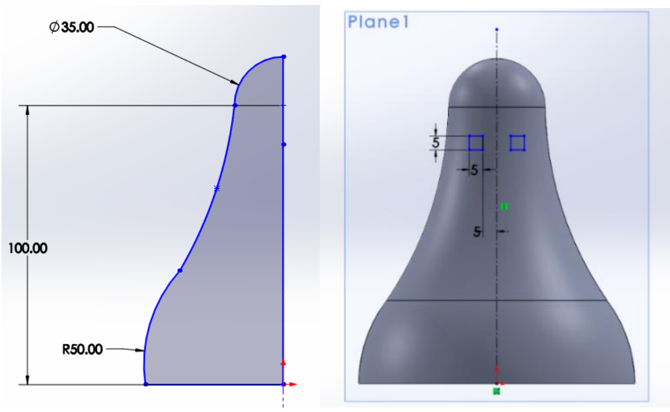
2. Creation of a 3D virtual object – CAD model

The development of a product in CAD software is a process that encompasses a series of activities, starting from the idea of a new product all the way to its market launch. It is also an interactive process that involves experts from various functional sectors within a company, as well as individuals external to that organization.

The 3D virtual model (Matryoshka Doll – a.k.a. babuška, Fig. 1) was created using the SolidWorks 2018 software package. The 3D model (product) – babuška, consists of two transitions in the form of radii, as well as two indentations representing the eyes, which are shaped like cubes. The process of creating a 3D product model in the software package involves considering the model itself as a technological entity (feature) that is modeled using a single operation.

Fig. 1 3D CAD model

The product component itself was created by revolving a pre-dimensioned contour around the central axis of symmetry (Revolve), as shown in Fig. 2a. To create the eyes of the Matryoshka Doll, an eye profile was required. It is important to note that when creating the profile path, a plane (Plane) was used for sketching the eye profile, positioned at a distance of 50 mm from the center, as depicted in Fig. 2b. To ensure the removal of excess material, the material removal option (Extrude cut) was used during the creation of the eyes.



(a) (b)

Fig. 2 Individual stages of creating the 3D product model - babuška: (a) creating and dimensioning the contour, (b) creating and dimensioning the indentations - eyes.

3. Creation of a 3D object – printing the CAD model to a realistic model

In order to perform the analysis, it is necessary to first convert the 3D virtual model into a physical object. The original format obtained in the SolidWorks software package was .SLDPRT, but to conduct the analysis, it needed to be converted to the .STEP format. During the conversion from the virtual model to the physical object - the product, additive manufacturing technology (3D printing) was used, and the material of the printed product was PLA (Polylactide).

PLA material possesses good characteristics, as it can withstand temperatures up to 60°C without deformation. Its melting point ranges from 120°C to 170°C, with a tensile strength ranging from 16 MPa to 117 MPa. The density of PLA is 1.24 g/cm³ [7, 8].

The Creality CR-6 SE 3D printer was used for printing the 3D model, with a room temperature of 24°C.

There were a total of 6 printed models:

- 3 red PLA models (1 model as it was printed, 1 model later colored with the pink glossy varnish, and 1 model later colored with the pink matte varnish).
- 3 blue PLA models (1 model as it was printed, 1 model later colored with the pink glossy varnish, and 1 model later colored with the pink matte varnish).

4. Creation of a 3D virtual object – 3D scanning of a real model

3D scanning using non-contact 3D scanner-tools has excellent properties, including high precision and fast measurement. The laser reflection of the surface of the scanned object, noise - speckles, and detection of the laser stripe's peak have a significant impact on the accuracy during part inspection. Camera calibration and scanner parameter adjustments have a great influence on the scanner's precision. It is necessary to calibrate the cameras to adjust certain parameters, such as lens distortion, laser tilt, camera focus, the angle between the camera axis and the scanner's linear motion, and the lighting level [9].

The cameras that detect reflected light automatically process the data in the computer, considering the linear propagation of light. In each individual scan, regions of shadows or dark zones may be present. Optical transmitters and receivers are devices used to transmit information in the form of light signals along optical fibers [10].

During the scanning process, the RangeVision Smart scanner was used, which utilizes monochromatic light and structured light technology. In order to scan all surfaces and achieve flawless geometric shape, a turntable was also employed in this experiment. The ScanCenter NG software connects individual parts based on corresponding positioners, resulting in a rough representation of the scanned surface geometry. The scanning process took place in a home environment at a temperature of 24℃. If the conditions had not been met, there might have been certain variations during the measurements, which is why it was necessary to perform the 3D scanning procedure in air-conditioned rooms. However, different models required scanning conditions.

4.1 Blue model

In order to perform a comparative analysis of the scanned and virtual 3D models, it is necessary to create a surface or solid model using the obtained point cloud. Light sources used in the field of 3D scanning must be monochromatic, stable, and long-lasting.

Before starting the operation of the 3D scanner, certain parameters need to be adjusted, such as the illumination level on a scale of 1 to 5, camera sharpness, and the number of scans per scanning session. The light source should maintain a constant level of illumination over time and during temperature changes in the room, as well as a consistent wavelength of the generated light.

In order to scan the entire model, it is necessary to scan it from multiple positions. The use of a turntable reduces the scanning process and time. In this study, the RangeVision turntable was used. Each sample, or model, was scanned under daylight conditions. The parameters and the number of elements used during the scanning of the blue-colored 3D model are shown in Table 1. In practice, there are no monochromatic light sources, but sources that generate light within a very narrow range of wavelengths.

Table 1. Scanning parameters – blue model

	Exposure	Number of scans	Number of scans per model	Number of created points representing CAD model
Models without lacquer	3	2	12	10007058
Model with pink glossy varnish	5	4	10	10546787
Model with pink matte varnish	5	4	10	9027171

From Table 1, one can observe that when scanning models without lacquer, a moderate level of illumination is required, while for models with glossy and matte lacquer, maximum illumination is needed. When scanning shiny surfaces, ambient light significantly affects the results by reducing the number of scanned elements due to strong reflections. For matte surfaces, the influence of illumination is identical to that of shiny surfaces, requiring maximum illumination to obtain a higher number of elements. In this case, there is significant dispersion of light rays, resulting in a lower number of detected points by the cameras, so it is necessary to increase the level of illumination to capture more points. During scanning, a problem occurred where point clouds overlapped, causing suboptimal data alignment. This phenomenon arose because the surface was identical from all sides except around the indentations – the eyes. The problem was resolved by carving a groove in the lower part that did not affect the scanning results but greatly aided in the scanning process.

4.2 Red model

The 3D scanners with structured light encounter difficulties when scanning shiny or dark objects. The scanning process is done in segments since no scanner has the capability to gather data in a single step. When operating the RangeVision Smart 3D scanner, the same parameters were set as in the case of the blue model to collect the most accurate data. It is possible to optimize the measurement settings in a way that minimizes the impact of poor scanning geometry, resulting in a more efficient acquisition of higher-quality point clouds. By adjusting the parameters, more precise model data can be obtained, increasing the number of scanned elements and reducing scanning time. We can choose a 360° rotation of the turntable to scan the entire object, depending on the material's structure and color, selecting the number of scanning positions accordingly. During the scanning of the red model, a problem of point cloud overlap occurred, and in this case, we resolved it in the same manner by carving a groove in the lower part of the model. Table 2 provides an overview of the adjusted parameters.

Table 2. Scanning parameters – red model

	Exposure	Number of scans	Number of scans per model	Number of created points representing CAD model
Models without lacquer	3	2	12	6915099
Model with pink glossy varnish	5	3	10	13783670
Model with pink matte varnish	4	3	10	7101.498

From Table 2, one can observe that when scanning a model without lacquer, a medium level of illumination is required, while for a model with glossy lacquer, a maximum level of illumination is needed. Ambient light, surface color and material have a significant impact during 3D scanning, as evident from Table 2. Due to the glossy surface, certain points are not captured in the scan, resulting in light scattering, which in turn leads to diffuse reflection. Therefore, it is necessary to increase the level of illumination in such cases.

5. Comparative analysis

This study presents a comparison of the deviation between the 3D virtual model and the scanned blue and red models of the same material, as well as the deviation between the 3D virtual model and the scanned blue and red models that were coated with glossy and matte pink lacquer. Product inspection based on CAD was performed by comparing the reconstructed model from scanned data with the original CAD model, enabling seamless integration of design with manufacturing control information such as tolerance of the CAD model itself [11].

It is important to note that during scanning, calibration of cameras, surface quality, roughness, and surface color had a significant impact, in addition to ambient light.

5.1. Red model

The scanned point cloud of points was generated and exported in the STL format, while the CAD model was exported in the .STEP format for the purpose of performing a comparative analysis. This analysis resulted in a color map representing tolerance deviations from the solid model. In the positive range, the maximum value was +0.7 mm, while in the negative range, the maximum value was -0.7 mm.

The deviations obtained during the comparative analysis depended significantly on the adjusted parameters. When scanning the red model, it could be observed that the model with a glossy coating experienced strong reflections during scanning. To achieve better results, i.e., a higher number of points, it was necessary to use the maximum level of illumination and perform more scans. The number of scanned elements for the glossy coating was 13783670, which was significantly higher compared to the matte coating and non-lacquered surfaces. This result was attributed to the significant amount of light that illuminated the object during scanning, leading to the occurrence of diffusion where the cameras detected a large number of reflected rays. In contrast, for the model with a base surface color, a moderate level of illumination was required, resulting in a considerably lower number of scans.

During the scanning of the non-lacquered model and the model with a matte coating, it was observed that the number of obtained elements was higher for the matte-coated model. This was because the surface structures itself was darker, requiring a greater amount of light and a larger number of scans.

Table 3 provides a comparative analysis with the CAD model, based on the scanned surfaces, after obtaining the computationally compatible digital model without lacquer, with glossy and matte lacquer.

Table 3. Results of the comparative analysis between the red model and the CAD model

	Extreme negative deviation	Extreme positive deviation
Models without lacquer	-0.35 mm	+0.6 mm
Model with pink glossy varnish	-0.25 mm	+0.4 mm
Model with pink matte varnish	-0.4 mm	+0.4 mm

From Table 3, it can be observed that the maximum deviation in the positive range occurs in the case of the model without lacquer, in the orange zone, with a value of +0.6 mm. The maximum deviation in the negative range occurs in the case of the model with matte lacquer, in the blue zone, with a value of -0.4 mm.
Based on the results of the comparative analysis, it is observed that the radii and certain elements such as indentations, openings, etc., have an impact on both positive and negative deviations, where the refraction of light occurs during the emission of rays.

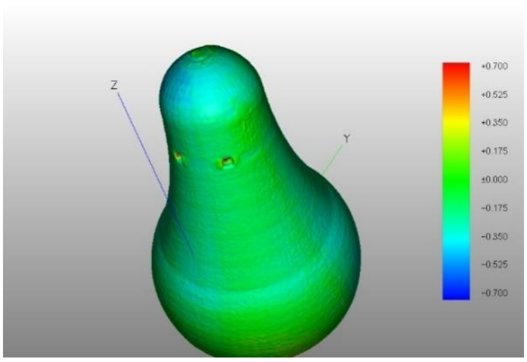


Fig. 3 Results of the comparison between the CAD model and the generated red model without coating

In Fig. 3, a representation of the maximum positive range deviation is provided, where it can be observed that it occurs in the concave region.

5.1. Blue model

After conducting a comparative analysis of the blue model with the generated model, a color map representing tolerance deviations from the solid model was obtained. In the positive range, the maximum deviation was +1 mm, while in the negative range, the maximum deviation was -1 mm.

The number of scanned points in the model with a glossy coating (10546787) was higher compared to the matte coating (9027171), while the scanning parameters were the same. In this case, significant scattering of light rays occurred, where the cameras detected a considerably smaller number of points if the illumination level was not maximal. Therefore, it was necessary to increase the illumination level in order to obtain more points. When scanning the model without any coating, it was observed that the required number of scans was half of those for the glossy and matte surfaces. Additionally, when using a moderate level of illumination, approximately the same number of elements was obtained as in the case of the model with a glossy coating. The deviations obtained by comparative analysis are shown in Table 4.

Fig. 4 provides the representation of the maximum deviation in the negative range, where it can be observed that it occurs in the area of the largest radius.

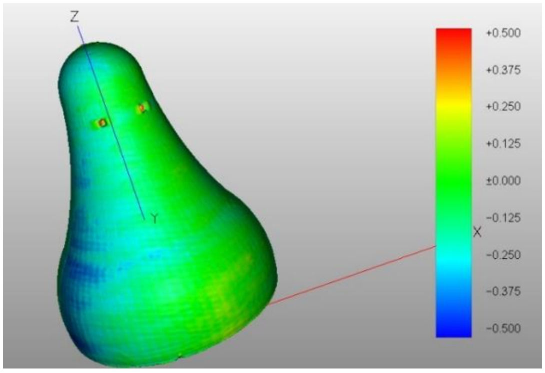


Fig. 4 The results of comparing the CAD model with the generated red model with a matte finish

Table 4. Results of the comparative analysis between the blue model and the CAD model

	Negative deviation	Positive deviation
Models without lacquer	-0.3 mm	+0.75 mm
Model with pink glossy varnish	-0.5 mm	+0.5 mm
Model with pink matte varnish	-0.6 mm	+0.6 mm

From Table 4, it can be observed that the maximum deviation in the positive range occurs in the case of the model without lacquer, in the red zone, with a value of +0.75 mm, whereas the maximum deviation in the negative range occurs in the case of the model with matte lacquer, in the blue zone, with a value of -0.6 mm.

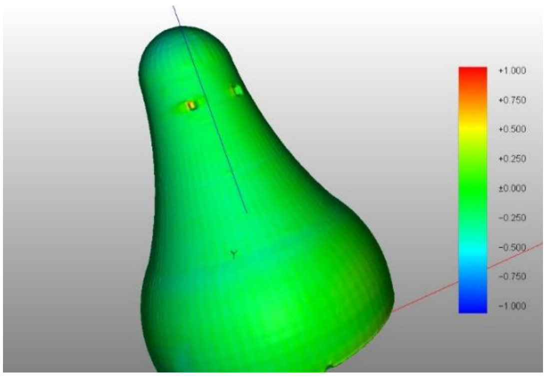


Fig. 5 Results of comparing the CAD model with the generated blue model without lacquer

Fig. 5 provides a depiction of the maximum positive deviation, showing that it occurs in the concave area.

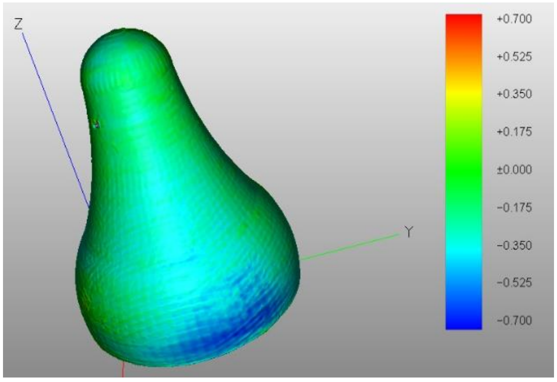


Fig. 6 The results of comparing the CAD model with the generated blue model with a matte finish

Fig. 6 provides the representation of the maximum deviation in the negative range, where it can be observed that is occurs in the area of the largest radius.

Based on the comparative analysis of the CAD model with the generated model, it is observed that the deviation is significantly larger in the case of the model without any coating, despite the number of elements being approximately the same as in the model with a glossy coating. In this case, the surface roughness factor and color have a significant influence.

Non-contact scanning is based on the principle where a source of laser light illuminates the object with parallel, horizontal, and angled lines, while cameras gather information and create a digital representation. During scanning, diffraction may occur. Diffraction happens when a light wave does not strike a surface, opening, or obstacle perpendicularly but at an angle, causing the light rays to deviate. During scanning, diffraction occurs, resulting in the appearance of colored circles or lines with dark regions in between. This phenomenon can also be observed with the naked eye [12].

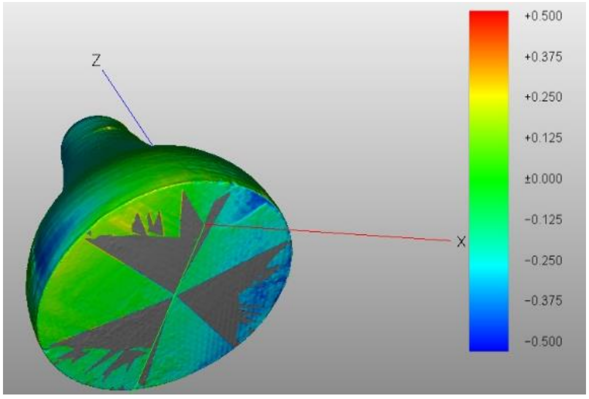


Fig. 7 The phenomenon of diffraction

In Fig. 7, the phenomenon of diffraction is observed, appearing in the form of triangles. In the region where diffraction occurs, it can be seen from the image that there is a significant positive deviation based on the color map on the right side. The phenomenon of diffraction occurs on surfaces where light waves are deviated from their original propagation direction, encountering an obstacle and creating a new propagation direction. In this case, the surface is flat, specifically in the lower part of the nested doll model. The occurrence of diffraction takes the form of triangles during the scanning of each model, both with and without coating.

5. CONCLUSIONS

Many factors affect the quality of the obtained 3D scanned point cloud, such as the geometry of scanned surfaces, surface roughness, color of scanned surfaces, scanner resolution, proper calibration procedure, surface color, ambient light, room temperature, and appropriate selection of scanned segments. During scanning, shadow regions or dark zones may be encountered, which occur as a result of linear propagation of light from the light source.

3D scanning technologies are potential tools for increasing productivity, accuracy, while simultaneously ensuring high product quality.

When scanning a model with glossy pink lacquer, it can be observed that the resulting polygonal mesh has more elements compared to the model without lacquer and with matte lacquer. Additionally, in this case, the lighting level is at its maximum, where more rays are reflected upon reflection, and the cameras detect and create the polygonal mesh. This is usually a file consisting of (x, y, z) coordinates often supplemented with black-and-white intensity or color for each measurement point.

After conducting a comparative analysis on the red and blue models made of the same material, having and not having a coating, it can be observed that the color of the material has a significant impact. In the case of the blue model, the maximum negative deviation occurs in the matte lacquer model at -0.6 mm, while the maximum positive deviation occurs in the model without lacquer at +0.75 mm. Based on the obtained results, it can be observed that the maximum negative deviation occurs in the model with a matte coating, confirming our suspicion that a darker surface color significantly affects the results and thus reduces the occurrence of a large number of reflected rays. In the case of the red model, the maximum negative deviation occurs in the matte lacquer model at -0.4 mm, while the maximum positive deviation occurs in the model without lacquer at +0.6 mm. The maximum positive deviation indicates that the material's structure influences the quality of the obtained results. It is observed that when scanning the model with a glossy coating, more precise results are obtained, despite the light scattering. The significant advantage is the high level of illumination, which results in a greater number of elements and more precise results.

Based on the conducted comparative analysis and the obtained results, it can be observed that color and surface shape have a significant impact in this study. When the rays are emitted, they can be parallel and horizontal until they come into contact with a surface that is inclined at a certain angle relative to the projection. This research has demonstrated that a lighter surface substrate, such as the case of a red color coated with glossy lacquer, provides better and more accurate results compared to a darker surface color.

When it comes to a complex model with both small and large radii, in order to achieve more precise results, it is advisable to use the red model with a glossy finish. It is recommended to perform the scanning at night to minimize the influence of external light during the scanning process, while also conducting multiple passes.

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