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Influence of Illumination Level and Number of Scans on the Dimensional Accuracy of 3D-Scanned Aluminum Parts

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***Abstract*—In this study, the influence of 3D scanning process parameters on the digitization accuracy of original aluminum parts with simple and complex geometries and glossy surfaces was investigated. The experimental analysis focused on examining the effects of illumination level and the number of scans per single rotation of the rotary table. Absolute and relative errors of diameter and height were used as accuracy metrics, obtained by comparing the scanned 3D models with reference values measured using a digital vernier caliper. The results demonstrated that the illumination level has a significant impact on scanning accuracy, particularly for the geometrically complex part, where the lowest absolute and relative error values were achieved at the highest illumination level. The analysis of the number of scans indicated that increasing the number of individual scans does not necessarily lead to improved accuracy; in fact, the highest error values were recorded at the maximum number of scans, especially for the complex part and the height dimension. A comparative analysis of the simple and complex parts revealed that geometric complexity and surface reflectivity significantly affect the stability and reliability of 3D scanning results.**

Keywords—3D scanning, absolute error, relative error, illumination level, number of scans

I. INTRODUCTION

The development of 3D scanning technologies has enabled rapid and highly accurate digitization of existing physical objects, significantly enhancing the processes of reverse engineering, quality control, and digital geometric reconstruction [1].

Modern optical 3D scanners enable the rapid acquisition of large amounts of spatial data from real-world objects and their integration into digital models with high geometric accuracy, which are widely applied in product inspection, quality management, and reverse engineering processes. However, the selection of an appropriate measurement volume and system configuration represents a critical factor, as larger volumes allow more efficient scanning of larger parts but may simultaneously lead to a reduction in the accuracy of the acquired data [2].

Although 3D scanning is well suited for reverse engineering of geometrically complex components, the achieved accuracy strongly depends on the quality of the generated point cloud and the surface reflectivity of the scanned object [3].

In the study conducted by Tóth and Živčák [4], a comparative investigation of the accuracy of the optical 3D scanner Steinbichler Comet L3D and the laser 3D scanner Creaform EXAscan was performed. The authors designed a dedicated reference specimen with simple geometry, without deep cavities or hard-to-access regions, in order to ensure comparable scanning conditions for both technologies. The specimen was scanned multiple times, and the resulting models were compared with the reference CAD model using VGStudio MAX software. Dimensional and geometric deviations were analyzed, and the results indicated differences in accuracy and deviation distribution depending on the scanning technology, illumination conditions, and surface characteristics of the object.

Helle and Lemu [3] analyzed the capabilities and limitations of 3D scanning in reverse engineering and quality control through an investigation conducted on a metal component with complex geometry, demonstrating that the accuracy of the resulting CAD models depends on point cloud quality, surface properties, and reconstruction methods.

In industrial applications, 3D scanning is increasingly employed for dimensional measurement, comparison with nominal CAD models, and inspection of geometrically complex parts, where conventional measurement techniques may be limited or insufficiently efficient. In the study by Antova and Tanev [5], the application of laser 3D scanning for the reconstruction of complex geometry of existing structures was demonstrated through point cloud processing, geometric element approximation, and the generation of an accurate CAD model within a Scan-to-CAD/BIM environment.

In study [6], the accuracy of 3D scanning was investigated through the analysis of dimensional errors obtained by comparing scanned models with the reference dimensions of two test specimens. Particular emphasis was placed on the identification and optimization of process parameters that significantly affect scanning accuracy.

In our previous experimental investigations, the influence of the number of scans on point cloud quality was analyzed for simple and complex geometries produced by additive manufacturing using PLA material. In those investigations, the illumination level was kept constant at its maximum value, while the influence of the scanning process was examined exclusively through variations in the number of individual scans during object rotation.

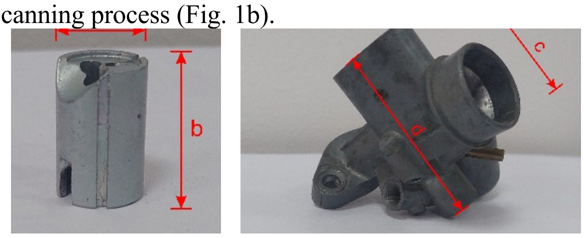
However, in industrial practice, original metal components with glossy and reflective surfaces are frequently encountered, whose optical characteristics pose an additional challenge for optical 3D scanning systems [3]. Glossy surfaces may cause reflections, sensor saturation, and noise in the point cloud, which directly affect the accuracy of geometric reconstruction and the dimensional precision of the scanned model. Under such conditions, in addition to the number of scans, the illumination level and the method of combining multiple scans acquired during a single rotation of the rotary table play a significant role.

The aim of this study is to extend previous research by focusing on the analysis of the influence of the number of scans per single rotation of the rotary table and the illumination level on the accuracy of 3D scanning of original aluminum parts with glossy surfaces. The investigation was conducted on parts with both simple and complex geometries. The accuracy of the obtained models was evaluated by comparing the diameter and height dimensions with reference values measured using a digital vernier caliper.

II. MATERIALS AND METHODS

A. Test Specimens

The investigation was conducted on original aluminum parts with glossy and reflective surfaces, and two types of geometry were analyzed: a simple and a complex part. The simple part consists of a cylindrical geometry with a central hole and a local recess, which introduces an additional geometric discontinuity and represents a potential source of error during optical 3D scanning (Fig. 1a). The complex part is a carburetor with a complex spatial geometry, characterized by a large number of transitions, curved surfaces, and internal channels, which poses a significantly greater challenge for the 3D scanning process (Fig. 1b).



(a) (b)

Fig 1. a) Simple geometry, b) Complex geometry

Due to differences in geometric complexity and surface accessibility, the simple part was scanned in two orientations, while the complex part was scanned in three orientations, in order to achieve better geometric coverage and reduce occlusion effects.

B. Reference Measurements

The reference values of the characteristic dimensions of the investigated parts were determined using a digital vernier caliper. The selected measured quantities were diameter and height, as they represent fundamental dimensions suitable for comparison between the scanned model and the physical object, as well as for the assessment of the dimensional accuracy of 3D scanning. Fig. 1a shows the characteristic dimensions of the simple part, where the diameter is denoted by symbol a and the height by symbol b, while in Fig. 1b, for the complex part, the diameter and height are denoted by symbols c and d, respectively.

Reference measurements were performed using a MarCal 16EWRi digital caliper (designation 4103402). Prior to the measurements, the instrument was calibrated using an appropriate gauge block, thereby ensuring the reliability and traceability of the measurement results. The digital caliper was connected to a computer, enabling automatic transfer and digital recording of the measured values, which reduced the possibility of manual data entry errors and ensured improved measurement repeatability. For each dimension, ten repeated measurements were performed under identical conditions and at the same characteristic locations. The arithmetic mean of the obtained values was adopted as the reference value, thereby reducing the influence of random errors and increasing the reliability of the reference data.

The obtained reference values were used as the basis for calculating the absolute and relative errors of the dimensions derived from the 3D scanned models, enabling a quantitative assessment of the scanning process accuracy as a function of the applied parameters.

C. Scanning Experiment Plan

The 3D scanning experiment plan was defined to enable a systematic analysis of the influence of key process parameters on the accuracy of the obtained 3D models. The variable factors considered were the illumination level and the number of scans per single rotation of the rotary table, while all other scanning process parameters were kept constant.

The illumination level was varied at three discrete levels (1, 3, and 5), whereas the number of scans per single rotation of the rotary table was varied at three levels (9, 12, and 18 scans). In this manner, a 3 × 3 factorial experimental design was established, allowing the evaluation of both the individual and combined effects of the considered factors.

The samples were labeled V1–V9 for the simple part (P) and V19–V27 for the complex part (S), with each label corresponding to a unique combination of experimental parameters. This experimental organization enabled direct comparison of the results and a quantitative analysis of the influence of the selected scanning parameters on the accuracy of dimensional measurements.

TABLE I. EXPERIMENTAL SCHEME

	Illumination Level			***Number of Scans per Rotation***			***Model Type***	
	1	3	5	9	12	18	P	S
V1	*			*			*	
V2		*		*			*	
V3			*	*			*	
V4	*				*		*	
V5		*			*		*	
V6			*		*		*	
V7	*					*	*	
V8		*				*	*	
V9			*			*	*	
V19	*			*				*
V20		*		*				*
V21			*	*				*
V22	*				*			*
V23		*			*			*
V24			*		*			*
V25	*					*		*
V26		*				*		*
V27			*			*		*

D. *3D Scanning Process*

The 3D scanning process based on the structured light principle involves projecting light patterns onto the object surface and capturing the reflected rays using cameras, while the spatial coordinates of surface points are determined by the triangulation method [7]. The accuracy and quality of the resulting point cloud largely depend on several factors, including system calibration, camera resolution and noise, triangulation angle, illumination conditions, as well as the optical properties and geometric complexity of the scanned object.

The 3D scanning procedure was carried out using a RangeVision Smart optical 3D scanner equipped with a rotary table. The investigated parts were placed on the rotary table, and during each rotation a predefined number of individual scans was acquired in accordance with the experimental plan. In this manner, uniform surface coverage of the object and consistent scanning conditions were ensured for all experimental variants. Using the ScanCenter NG 2022.1 software in combination with the scanner, the scanned part was obtained in the form of a point cloud. After the scanning process, individual scans were aligned and merged based on corresponding positional information, resulting in a point cloud representing an approximation of the scanned surface geometry. The merging of multiple scans improves surface coverage and reduces occluded regions of the scanned object. However, the final dimensional accuracy may be affected by the quality of the scan registration process. Small alignment deviations between overlapping scans or noise in the captured data may accumulate during the merging procedure, which can introduce additional geometric deviations in the resulting model, particularly for complex parts and reflective metallic surfaces.

The ScanCenter NG software enables automatic registration and merging of point clouds into a unified 3D model, as well as the execution of various measurement operations, including point-to-point, point-to-surface, and mesh-to-mesh measurements. Examples of point clouds and generated 3D models for the simple and complex parts are shown in Fig. 2 and Fig. 3.

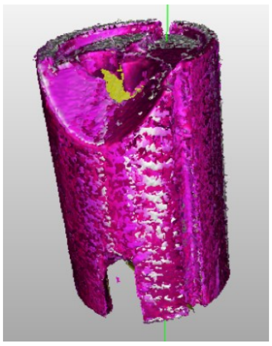


Fig. 2. Point cloud – simple part

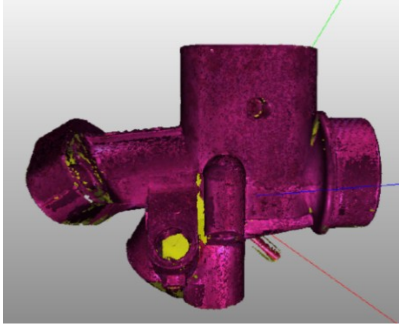


Fig. 3. Point cloud – complex part

E. *Accuracy Evaluation Method*

The evaluation of 3D scanning accuracy was performed by comparing the dimensions obtained from the scanned 3D models with the reference values measured using a digital vernier caliper. Absolute error and relative error were used as the accuracy assessment criteria, enabling a quantitative analysis of deviations as a function of the applied scanning parameters.

The absolute dimensional error is defined as the absolute value of the difference between the dimension measured on the scanned model and the reference value [6], according to the following expression:

$$\Delta = \left| X_{scan} - X_{ref} \right| \quad (1)$$

where X_{scan}vrepresents the dimensional value obtained by 3D scanning, and X_{ref} r denotes the reference dimensional value obtained by conventional measurement.

The relative error is expressed as the ratio of the absolute error to the reference dimensional value [8], expressed in percentage, and is calculated according to the following expression:

$$\delta = \frac{\left| X_{scan} - X_{ref} \right|}{X_{ref}} * 100\,\% \tag{2}$$

For each combination of scanning parameters, absolute and relative errors were calculated for both diameter and height, after which the mean error values were determined. The obtained results were used to analyze the influence of the illumination level and the number of scans per single rotation of the rotary table, as well as to compare the scanning accuracy between the simple and complex parts.

In this study, the criterion of optimality was defined as the minimum mean error value, with both absolute and relative errors being considered, in order to identify the most favorable 3D scanning conditions.

III. RESULTS

Fig. 4 illustrates the influence of the illumination level on the mean absolute error of diameter and height for the simple and complex parts. It can be observed that the absolute error values vary depending on the geometry and the considered dimension, with the complex part exhibiting more pronounced error variability compared to the simple part.

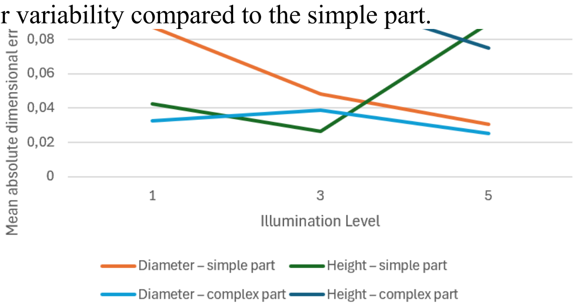


Fig. 4. Influence of illumination level on the mean absolute error of diameter and height for the simple and complex parts

Fig. 5 shows the dependence of the mean absolute error on the number of scans per single rotation of the rotary table. The results indicate the existence of an optimal number of scans for certain dimensions, while an increase in the number of scans does not lead to error reduction, particularly in the case of the complex part.

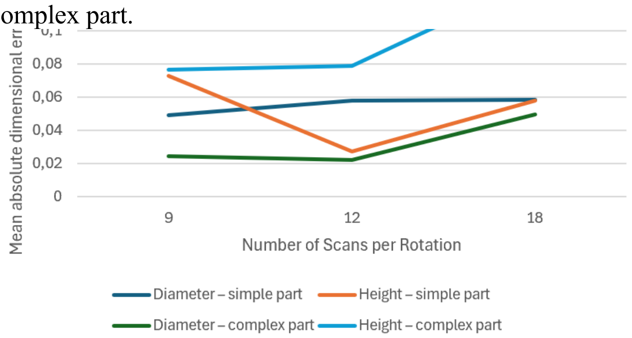


Fig. 5. Influence of the number of scans per single rotation on the mean absolute error of diameter and height for the simple and complex parts.

Minimum and maximum values of the absolute error were identified based on the presented diagrams.

Fig. 6 presents the dependence of the mean relative error of diameter and height on the illumination level for the simple and complex parts. The diagram illustrates variations in relative error as a function of the applied illumination conditions, with noticeable differences in the behavior of relative error between the simple and complex parts, as well as between the analyzed dimensions.

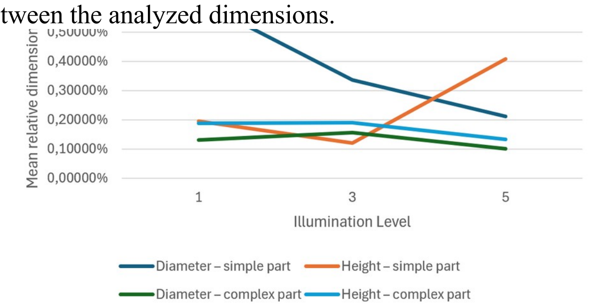


Fig. 6. Dependence of the mean relative error of diameter and height on the illumination level for the simple and complex parts

Fig. 7 illustrates the dependence of the mean relative error of diameter and height on the number of scans per single rotation of the rotary table. The diagram enables a comparative analysis of the influence of the number of scans on the relative error for the simple and complex parts, revealing that variations in the number of scans affect the relative error differently depending on the geometric complexity and the considered dimension.

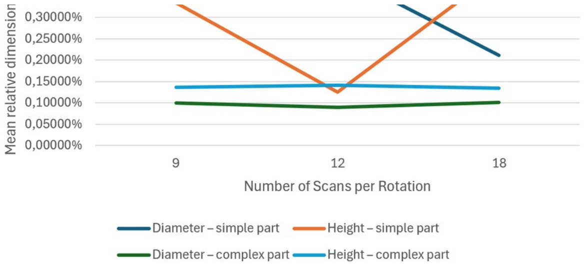


Fig. 7. Dependence of the mean relative error of diameter and height on the number of scans per single rotation for the simple and complex parts

IV. DISCUSSION

The analysis of the obtained results indicates that the accuracy of 3D scanning strongly depends on the combination of process parameters, primarily the illumination level and the number of scans per single rotation of the rotary table, as well as on the geometric complexity of the scanned part. A particular challenge in this study arises from the fact that the analyzed specimens are original aluminum parts with glossy and reflective surfaces, whose optical characteristics can significantly affect the quality of the acquired data and the scan registration process.

A comparative analysis of the simple and complex parts reveals that geometric complexity has a pronounced influence on the stability of scanning results. The complex part exhibits higher variability of both absolute and relative errors, especially for the height dimension, which can be attributed to the presence of a large number of curved surfaces, openings, and transitional regions. These features hinder stable point detection and increase the sensitivity of the scanning process to parameter variations. In contrast, the simple part, characterized by predominantly cylindrical geometry and well-defined edges, demonstrates more uniform error behavior, particularly for the diameter dimension. In addition to geometric complexity, the size of the scanned surface also plays an important role in the dimensional precision of the scanning process. Larger scanned surfaces generally provide a greater number of measurable points and overlapping regions between individual scans, which improves the stability of scan registration and reduces the influence of local noise in the point cloud. Consequently, a more stable alignment of scans can contribute to improved dimensional precision of the reconstructed model. However, when the scanned surface contains complex geometrical features or reflective regions, the benefits of larger surface coverage may be partially reduced due to occlusions, reflections, or difficulties in detecting stable surface features. The influence of the illumination level exhibits different effects depending on the geometry and the analyzed dimension. For the complex part, increasing the illumination level generally contributes to a reduction in both absolute and relative errors, indicating that higher illumination provides improved lighting of complex surfaces and reduces shadowing in critical regions. This leads to enhanced point cloud quality and increased stability of individual scan registration. For the simple part, however, the effect of illumination is not unambiguous. While a decreasing error trend with increasing illumination is observed for the diameter dimension, the height dimension shows an increase in error at the highest illumination level, suggesting increased sensitivity of simpler geometry and reflective surfaces to intense lighting conditions.

The analysis of the influence of the number of scans per single rotation indicates that increasing the number of individual scans does not necessarily result in improved accuracy. For the simple part, optimal results are achieved at a low or medium number of scans, whereas an increase in error —particularly for the height dimension—is observed at the highest number of scans. This effect is even more pronounced for the complex part, where the highest error values, especially the relative error of height, occur at the maximum number of scans. Such behavior suggests the possibility of error accumulation during the registration of a larger number of scans, as well as increased sensitivity of complex and reflective geometries to non-ideal alignment conditions. A comparative analysis of absolute and relative errors shows that both metrics reveal the same fundamental trends in system behavior, while relative error enables a clearer comparison between the simple and complex parts, independent of nominal dimensions. It is particularly evident that relative error further highlights the increased sensitivity of the height dimension of the complex part to variations in process parameters. The obtained results are consistent with findings reported in the literature, which emphasize that reflective metallic surfaces and geometrically complex parts represent a particular challenge for optical 3D scanning systems, and that a higher number of scans does not automatically guarantee improved accuracy due to registration issues and the occurrence of noise in the point cloud.

Similar accuracy-related issues in optical 3D scanning have been described in the literature, where it has been highlighted that reflective metal surfaces, object geometric complexity, and point cloud processing procedures have a significant influence on the occurrence of dimensional and geometric deviations of scanned models with respect to the reference geometry [9].

V. CONCLUSIONS

In this study, the influence of illumination level and the number of scans per single rotation of the rotary table on the accuracy of 3D scanning of original aluminum parts with simple and complex geometries was investigated. The accuracy was evaluated based on the absolute and relative errors of diameter and height.

The absolute error results showed that, for the simple part, the minimum diameter error was achieved at illumination level 5 (0.0304 mm), while the maximum value was recorded at level 1 (0.0871 mm). For the height of the simple part, the minimum error was 0.0265 mm at illumination level 3, whereas the maximum value of 0.0895 mm occurred at level 5. For the complex part, the lowest absolute errors of both diameter and height were obtained at illumination level 5 (0.0252 mm and 0.0749 mm, respectively).

The analysis of the number of scans indicated that increasing the number of scans does not lead to error reduction. For the simple part, the minimum diameter error was achieved at 9 scans (0.0492 mm), while the minimum height error was observed at 12 scans (0.0275 mm). For the complex part, the highest error values—particularly for height (0.1304 mm)—were recorded at 18 scans. Relative error exhibited trends consistent with those observed for absolute error. The lowest relative errors for the complex part were achieved at illumination level 5 (0.10134 % for diameter and 0.13399 % for height), while the highest relative height error was recorded at 18 scans (0.23333 %).

Based on the obtained results, it can be concluded that illumination level is a key parameter affecting the scanning accuracy of complex aluminum parts, whereas an excessive number of scans may negatively influence accuracy, particularly in the case of complex geometries and reflective surfaces. The presented findings may have practical applications in reverse engineering and quality control processes of industrial metal components.

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