ASSESSMENT OF PHOTOGRAMMETRY TECHNIQUES FOR 3D MODEL ACQUISITION: A COMPARATIVE STUDY ON THE ACCURACY AND SUITABILITY OF SCANNED MODELS COMPARED TO CAD REFERENCES

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DOI: 10.17973/MMSJ.2024_11_2024029

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This paper presents a comprehensive evaluation of the accuracy of 3D scanning methods using various devices and software to generate 3D models. The resulting models were compared to their corresponding Computer-Aided Design (CAD) models to quantify discrepancies. The primary objective was to assess potential errors, benefits, and limitations of each scanning method, providing insights for future research and development. A switch, chosen as the test object for its moderate complexity and size, enabled a thorough assessment under realistic conditions. The analysis reveals the strengths and limitations of each scanning method, guiding researchers and developers in selecting the most suitable techniques for specific applications. Additionally, the study underscores the importance of device and software parameters on the accuracy of 3D models, offering a comprehensive evaluation of effective techniques for 3D model.

KEYWORDS

3D scanning, photogrammetry, CAD models, scanning model, comparing

1 INTRODUCTION

In the domain of technological advancement, few innovations have garnered as much attention and potential as 3D scanning. This transformative technology, capable of accurately capturing and reconstructing physical objects in three-dimensional space, has quickly become a fundamental element of contemporary engineering, design, and research. This discourse investigates the significance and versatility of 3D scanning, shedding light on its multifaceted applications and critical role in shaping various fields. The primary appeal of 3D scanning stems from its unparalleled ability to bridge the gap between physical and digital domains with remarkable precision. Through the utilization of diverse sensors, such as structured light, laser technology, and photogrammetry, 3D scanners meticulously capture the intricate geometries and surface characteristics of objects, generating digital replicas that faithfully reflect their real-world counterparts. This capability not only transforms our perception and interaction with physical objects but also unlocks a plethora of opportunities for innovation and exploration. The impact of 3D scanning resonates across a wide range of domains, each benefiting from its distinct capabilities and applications. In sectors like manufacturing and industrial design, 3D scanning acts as a cornerstone for product development, facilitating precise measurements, quality assurance, and rapid prototyping. Similarly, fields like archaeology and cultural heritage preservation utilize 3D scanning to digitally conserve artifacts and monuments, safeguarding invaluable cultural legacies for posterity. Additionally, the flexibility of 3D scanning extends beyond conventional boundaries, infiltrating diverse fields including healthcare, entertainment, and forensics. For instance, in the medical realm, 3D scanning streamlines the customization of prosthetics and orthotics, improving patient outcomes and quality of life. In the realm of entertainment and virtual reality, 3D scanning empowers creators to seamlessly integrate real-world elements into immersive digital experiences. Even in forensic science, 3D scanning plays a pivotal role in documenting crime scenes and analyzing evidence, providing investigators with crucial insights and data. In essence, the applications of 3D scanning are as broad as they are profound, with each new utilization scenario pushing the boundaries of what is achievable. Whether it's meticulously restoring historical artifacts, optimizing manufacturing processes, or crafting immersive digital landscapes, 3D scanning remains at the forefront of innovation and exploration. The subsequent sections will delve deeper into the specific applications of 3D scanning, examining the intricacies of its implementation and the unique challenges and opportunities it presents. This article will unravel the myriad ways in which 3D scanning continues to influence our world, propelling us closer to a future where the distinctions between the physical and digital realms become increasingly blurred.

2 SCANNING

Object scanning or 3D scanning is a complex process used to capture the complex geometry, surface texture, and appearance of physical objects or environments, thereby creating digital representations in three-dimensional (3D) space. Its applications span a wide spectrum, from industrial design and engineering to cultural heritage conservation and beyond [Li 2023]. The essence of 3D scanning lies in its ability to faithfully reproduce the physical world in digital format, providing seamless integration between physical objects and virtual environments. The primary purpose of object scanning is to accurately capture complex details, dimensions, and surface characteristics of objects or environments [Gates 2006]. This level of accuracy and realism enables a wide range of applications across industries and disciplines, making 3D scanning a valuable tool for tasks such as product design, quality control, documentation, analysis, visualization, and preservation. One of the key benefits of 3D scanning is its ability to capture complex geometries and irregular shapes that may be difficult or impossible to measure using traditional methods. By creating digital copies of physical objects with high accuracy, 3D scanning allows accurate measurement, analysis, and visualization of objects in a virtual environment [Linder 2019]. In industrial design and manufacturing, 3D scanning is used for tasks such as reverse engineering, quality control, rapid prototyping, and creating digital duplicates of products or components. By scanning physical prototypes or existing parts, designers and engineers can quickly capture and modify complex geometries, verify dimensions, and ensure product quality and consistency.

2.1 Methods of scanning

In the realm of 3D scanning, various methods are employed to capture the intricate details of physical objects in three-dimensional space. These methods encompass a diverse range of technologies and techniques, each with its own principles and applications. From laser scanning and structured light to photogrammetry and ultrasound, these methods offer unique approaches to digitizing the physical world with unparalleled accuracy and precision.

Some common scanning object technologies include:

- Laser scanning involves emitting laser beams onto an object or surface and measuring the time it takes for the laser to return to the scanner. This data is then used to generate a 3D point cloud, which represents the object's geometry in high detail. Laser scanning has been a key technology in various fields, including image forming apparatus [Arimoto, 1989], microscopy, photography, and production control in the paper and plastics industry [Clarke 1971]. The technology has been used to generate high-quality microscopic images, create electrical analog signals of imagery in a serial manner, and enable reliable high-speed routine scanning for production control [Gabriele 2015].
- Structured light scanning involves projecting a pattern of light onto an object and capturing its deformation using one or more cameras. [Schipper 2024]. The distortion of the pattern provides in-depth information used to reconstruct a 3D model of the object [Zhang 2016]. Structured light scanning, a technique used for 3D reconstruction, has been enhanced through various methods [Chen 2015] proposed a system for 3D face scanning, improving accuracy and efficiency. Alsa a technique was developed for 3D surface reconstruction using line scan cameras and structured light, achieving high-quality reconstructions [Lilienblum 2014]. With the help of scanning, the problems of the effect of indirect lighting on mirror surfaces were addressed, introducing a combined coding method for high-quality. dense reconstruction [Gupta 2011], simplified the determination of light planes during structured light scanning, without the need for explicit projector calibration, maintaining reconstruction accuracy.
- Photogrammetry involves capturing multiple photographs of an object or scene from different angles and using software to analyze these images to reconstruct a 3D model. It relies on the principles of triangulation to determine the position of points in 3D space [Awange 2013]. Photogrammetry, a technique for non-direct 3D coordinate measurement using 2D photographic images, has a wide range of applications. It is used in the measurement of gravity deformation of antennas, analysis of photogrammetry data from ISIM mockups, underwater photogrammetric verification of nuclear fuel assemblies, and spacecraft optical bench and ground support equipment measurement [Pilar 2020].
- Computed Tomography (CT) scanning, also known as computerized axial tomographic (CAT) scanning, is a powerful imaging technique that provides detailed cross-sectional images of the body. It has been widely used in various medical fields, including the orbit where it can visualize normal tissues and pathological processes with high precision. The technique's ability to produce three-dimensional images has made it a valuable tool in diagnosing and identifying abnormalities, such as tumors. Despite its potential, challenges exist in replicating the excellent results achieved in medical scanners, particularly in industrial radiography.
- 3D Scanning with Depth Sensors, such as time-of-flight cameras or structured light sensors, can capture depth information about objects and environments, enabling the creation of 3D models. A range of studies have explored the use of depth sensors for 3D scanning. A new underwater was introduced 3D scanning device with high accuracy potential, particularly in offshore environments[Bräuer-Burchardt 2022]. Developed a solution for fast microscale 3D reconstruction using a low-cost depth sensor, achieving mm-level accuracy [Carey 2017].
- Ultrasonic scanning uses ultrasonic waves to measure distances and create 3D images of objects. It is commonly used in non-destructive testing (NDT) applications for inspecting materials and structures. Ultrasonic scanning has been explored in several studies: for testing using ultrasonic energy, which involved scanning a focused ultrasound beam and rescanning a region of interest at different depths [Cargill 1980].
- Magnetic Resonance Imaging (MRI) scanning is a non-invasive medical procedure that uses a combination of a strong magnetic field and radio waves to create detailed images of the inside of the body. It is a safe and painless procedure that does not use ionizing radiation, making it suitable for repeated use. The images produced by MRI can be manipulated to highlight specific tissue characteristics, such as fat content or hydration, and can be used to diagnose a variety of diseases and conditions. The procedure typically lasts between 20 to 90 minutes, depending on the area being imaged [Stodkilde-Jorgensen 2018].

These scanning object technologies vary in their principles of operation, level of accuracy, resolution, and suitability for diverse types of objects or environments. Depending on the specific requirements of a project.

2.2 Related works

A digital copy of an object is an important tool in today's world. It allows you to virtually reproduce a real object in three-dimensional space. One of the key steps in creating a digital twin is the 3D scanning process [Savakar 2018].

For creating digital twins on paper was used the process of 3D scanning using photogrammetry, including the steps involved in the 3D model reconstruction process and the main algorithm used. It also highlights the importance of capturing images from specific angles and elevations to ensure a good percentage of overlap for feature extraction and matching [Choi 2020]. Additionally, it mentions the impact of the nature of the object on the quality of the results, particularly for shiny, transparent, and featureless objects. The main objective of the system is to convert 2D images into a 3D model. The paper discusses the increasing popularity of 3D technologies in research and provides comparative analyses of multiple photogrammetry reconstructions for creating 3D models, along with the planned research using the reconstructed 3D models for various purposes [Reljic 2019]. The work describes the development of an immersive virtual reality application for the Imperial Cathedral in Konigslutter, integrating 360° panoramic photographs within the virtual environment as a novel form of visualization. The workflow to produce the VR experience of the Kaiserdom is detailed, including data acquisition, 3D modeling, hardware requirements, and testing [Lamb 2018]. The paper emphasizes the potential of integrating different kinds of data, such as real-time 3D visualization and HDRI panoramic photography, to build immersive experiences for cultural heritage preservation and education [Walmsley 2020]. Also, there was discussed the connection between technological advancements and the quality of life, emphasizes the advantages of the lost-wax casting method, and highlights the significance of three-dimensional printing as a major innovation in sculpture-making in the paper [Sargentis 2022]. [Ntoa 2014] explored the use of scanning in different contexts. Some works focus on the development of a Scanning Single Shot Detector for math in document images, while Ntoa discusses scanning-based interaction techniques for motor impaired users. [Gates 2006] presents a method for detecting scans at the ISP level, with a high level of accuracy. [Holzer 2022] provides a historical perspective on scan processing, particularly in the context of analog electronic image manipulation. The other studies collectively highlight the diverse applications and historical significance of scanning technology [Kristaly 2021]. The research papers discussed in this review include a study on distributed code behavior vulnerability with a fuzzy scanning algorithm based on machine learning [Su 2023] research on three-dimensional scanning path planning of casing parts based on an industrial robot [Li 2023] and an investigation on the impact of scanning strategy on the accuracy of complete-arch intraoral scans by [Mai 2022]. Each paper addresses different aspects of scanning and vulnerability detection technologies. The first paper proposes a distributed code behavior vulnerability fuzzy scanning algorithm utilizing machine learning to improve accuracy and reduce scanning time. The second paper focuses on automatic scanning path planning for casing parts to enhance scanning efficiency and quality. The third paper evaluates the accuracy of full-arch intraoral scans using different scanning strategies and segmental scan methods, suggesting that segmental scans and merge methods with two scan parts may be a reliable alternative to single scan methods for full-arch intraoral scans [Lee 2021]. Overall, the differences among these articles lie in their specific focus areas, methodologies, and applications within the field of scanning technology and vulnerability detection. Each paper presents unique findings and contributions to the existing body of knowledge in their respective domains [Ntoa 2014].

The next one important step is transferring 3D models to the developing area for creating digital shadow or twin. In general, the most used software programs are Unity Real-Time Development Platform and Unreal Engine. There is described the development and features of the GEARS visualization framework, including its use of game engines like Unity and Unreal Engine, its programming capabilities, and its interface with the LAMMPS simulation engine [Martinez-Ruedas et al., 2024], with the goal of making immersive scientific computing accessible to a broad research community in one of the papers [Horton 2019]. Also, UnrealROX is an extremely photorealistic virtual reality environment for generating synthetic data for various robotic vision tasks, providing features such as visually plausible grasping system, controlling robotic hands and bodies with commercial VR setups, sequence recorder and playback components, multi-camera component, and open-source code, assets, and tutorials [Kang 2024]. The system decouples the recording and data generation processes to achieve high framerates when gathering data in Virtual Reality without decreasing performance, and the outcome demonstrates the potential of using embodied agents in VR for simulating robotic interactions and generating synthetic data for training data-driven methods [Martinez-Gonzalez 2020]. The summary of the paper is that it presents a calibration procedure for achieving correct artificial light distribution in Unreal Engine 4, evaluating the effects of different parameters on light distribution, and confirming the ability of UE4 to replicate luminance and illuminance distribution in a complex environment [Scorpio 2022]. The paper discusses the development and features of the GEARS visualization framework, including its use of game engines like Unity and Unreal Engine, its programming capabilities, and its interface with the LAMMPS simulation engine, with the goal of making immersive scientific computing accessible to a broad research community [Horton 2019].

2.3 Methods which are used in research

In the manufacturing environment, it is important to use efficient and accurate scanning methods to obtain data about objects and production processes. Among the various scanning methods, such as 3D Scanning with Depth Sensors, Photometry, and Laser Scanning, are crucial for manufacturing.

The 3D Scanning with Depth Sensors method uses depth sensors to create a three-dimensional model of the object. This method is fast and accurate, allowing for the rapid scanning of many objects in the manufacturing environment [Ziegler 2018]. The use of this method enables effective monitoring of the production process and enhances product quality. Photometry uses light reflection analysis to create three-dimensional models. This method provides detailed data on object surfaces with different properties and textures. Manufacturing can utilize this method for quality control and modeling tasks. Laser Scanning uses laser to measure objects and create three-dimensional models. This method is known for its high accuracy and scanning speed, making it ideal for use in manufacturing. Laser Scanning provides detailed geometric information about objects and production processes. The main characteristics are shown in Table 1.

Table 1. Comparison of methods

Method	Preci-sion [mm]	Range	Availa-bility	Principle
3D Scan-ning with Depth Sensors	1≤10 mm	Limited to a few meters	Depth sensors are relatively accessible and come in various forms.	The sensors measure the time it takes for emitted light to bounce back from the object's surface.
Photo-gram-metry	1≤10 mm	Moderate, limited to a few meters.	Accessible and cost-effective	Photometry relies on capturing light intensity variations from viewpoints.

Comparing these three scanning methods, Laser Scanning is the most precise and fastest method, providing high-quality data for manufacturing. 3D Scanning with Depth Sensors and Photometry are also effective methods that can be used in manufacturing for various tasks. Therefore, the use of 3D Scanning with Depth Sensors, Photometry, and Laser Scanning methods in manufacturing will help improve productivity, quality control, and manufacturing accuracy, making them vital for modern manufacturing processes.

2.4 Devices and software for scanning

During the scanning process, the selection and utilization of devices and software plays a crucial role in achieving the best possible results. When opting for phones, tablets, or separate scanners, several key characteristics must be taken into consideration.

For mobile devices, such as phones and tablets, the following characteristics are essential for scanning purposes:

- High-resolution cameras and superior image sensors enable the capture of clearer and more detailed scans, which is critical for accurate model reconstruction.
- Fast processors and sufficient Random Access Memory (RAM) are necessary for efficiently handling scanning software and processing large amounts of data.
- Ample storage space is required to store scanned files and data without compromising device performance or risking memory overflow.
- Devices with reliable connectivity options, such as Wi-Fi, Bluetooth, and USB, are essential for transferring scanned files to other devices or cloud-based storage platforms.

By considering these characteristics, users can optimize their device selection and ensure optimal performance during the scanning process.

Table 2. Parameters of selected device (phone)

Devices	Camera parameters	Processing power	Connectivity
iPhone 15 Pro	48MP Main: 24 mm, ƒ/1.78 aperture	Apple A17 Bionic chip	USB 3.2 Gen 2 Type-C port. Wi-Fi 6E Bluetooth 5.3

When selecting separate scanners for optimal performance, the following characteristics are crucial considerations:

- Higher resolution scanners can capture more detailed and accurate scans, which is essential for achieving high-quality model reconstruction.
- The frame rate, a critical aspect of scanning technology, plays a significant role in determining the quality and speed of the scanning process. A higher frame rate can facilitate faster scanning and improved image quality.
- Scanners with higher color depth capabilities can capture a wider range of colors and shades, resulting in more vivid and realistic scans. This is particularly important in applications where color accuracy is paramount.
- Scanners equipped with multiple connectivity options, such as USB, Ethernet, and wireless connectivity, offer flexibility in how scanned data can be transferred, allowing for greater convenience and ease of use.

By carefully considering these key characteristics when selecting devices and software for scanning, users can ensure optimal performance, efficiency, and accuracy in their scanning processes.

Table 3. Description of selected devices(scanner)

Devices	Resolution	Frame Rate	Color depth	Connectivity
3Dmaker proseal light.	0.05mm	10fps	24-bit color scan	USB Interface: USB 2.0

There are several 3D scanning apps and software available that are compatible with phones and tablets, allowing users to capture 3D models and objects using the device's camera. Some popular 3D scanning apps include:

1. Unreal Reality Scan is a 3D scanning and augmented reality app developed by the company called "Unreal Reality." The app allows users to create detailed 3D scans of real-world objects and environments using their smartphone or tablet camera. The scans can then be used for various purposes such as 3D modeling, AR/VR content creation, animation, and more.

2. Reality Capture, created by Capturing Reality, is a state-of-the-art photogrammetric software used for 3D scans. It reconstructs objects and scenes of any size from images or laser scans. It yields 3D scans with accuracy and mesh quality, often faster than competing software. The software is widely used in various industries, including gaming, visual effects, film, surveying, architecture, engineering, construction, and cultural heritage.

Advantages of using 3D scanning software compatible with phones and tablets include: Mobile 3D scanning apps allow users to capture 3D models and objects on the go, without the need for expensive and bulky scanning equipment; apps make it easy for anyone to create 3D models using their phone or tablet, providing a user-friendly and intuitive interface for beginners and professionals alike; some 3D scanning apps offer real-time feedback and visualization capabilities, allowing users to see the scanned object in 3D as they capture it, ensuring accuracy and quality; many 3D scanning apps offer integration with 3D modeling software, 3D printers, and other tools for further editing, processing, and sharing of 3D models.

3 METHODOLOGY

The primary objective of this research is to investigate and evaluate various scanning methods utilizing distinct devices and software, with the goal of comparing the accuracy of generated 3D models with their corresponding Computer-Aided Design (CAD) models. This study aims to thoroughly examine the potential errors, advantages, and disadvantages of each scanning method, thereby providing a comprehensive understanding of the most effective and reliable techniques for future research and development purposes.

To facilitate a comprehensive evaluation, a specific object was chosen for scanning (Fig. 1). The switch was selected due to its moderate complexity and size, allowing for a thorough assessment of each scanning method's performance under real-world conditions [Zidek 2021].

The proposed scanning methods will be employed to capture 3D models of the switch, which will then be compared with their CAD counterparts to quantify the accuracy of each scanning method. The results of this analysis will provide valuable insights into the strengths and limitations of each scanning method, enabling researchers and developers to select the most suitable technique for their specific applications.

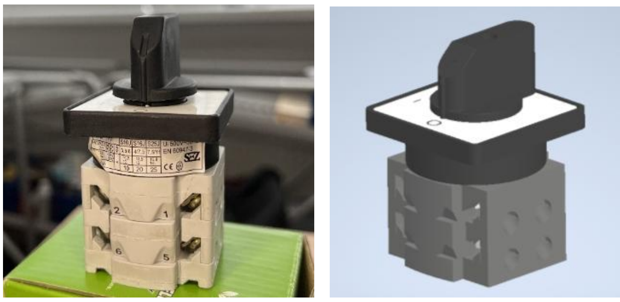

Figure 1. Scan model – Real assembly (left), CAD model (right)

To optimize the creation of 3D models through 3D scanning, a series of three experiments were conducted. Each experiment utilized a unique set of devices with distinct parameters, thereby allowing for a comprehensive evaluation of the impact of these variables on the resulting 3D models. Furthermore, to broaden the scope of the comparison and account for the diverse methods used by various software, multiple 3D model generation software packages were employed. These software tools operate on distinct principles for generating 3D models, thereby enabling a nuanced analysis of their strengths and limitations.

Furthermore, our objective is to investigate and propose various scanning methods for object capture, with a focus on the optimal approach. Specifically, we have developed three distinct scanning methods:

- Circular Scanning: In this method, the object is scanned at a single level, without changing the height. This approach allows for a thorough examination of the object's surface geometry at a fixed elevation (Fig. 2).

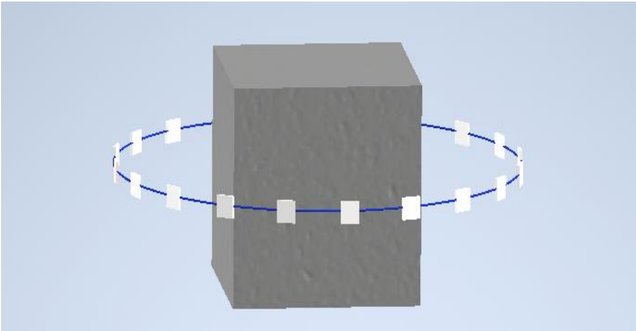

Figure 2. Circular scanning

- Spiral Scanning: In this method, the object is scanned at multiple levels, with the camera moving in a spiral pattern to capture data from varying heights. This approach enables the creation of a more detailed and comprehensive 3D model (Fig. 3).

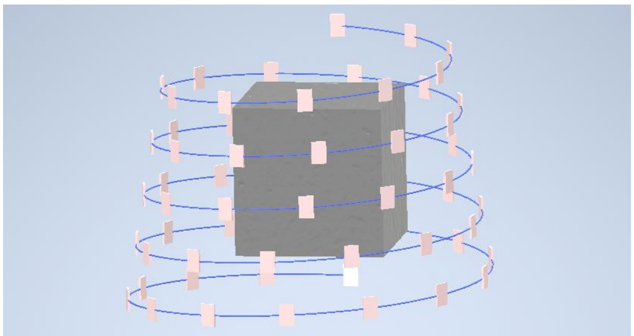

Figure 3. Spiral scanning

- Random Scanning: In this method, photos are taken from arbitrary heights and distances from the object, allowing for a more flexible and unstructured approach to scanning. This method provides a baseline for comparison with the more structured circular and spiral scanning methods (Fig. 4).

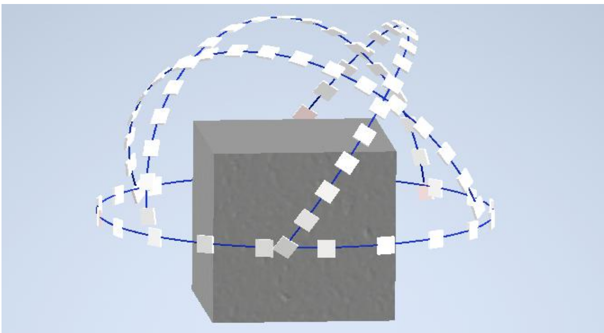

Figure 4. Random scanning

These proposed scanning methods will enable us to evaluate the effectiveness of each approach and determine the most suitable method for capturing high-quality 3D models of objects.

3.1 Photogrammetry

Two photogrammetry software packages, Reality Scan and Reality Capture, were selected for comparison. Although both software shares similar principles of operation, they exhibit distinct differences in terms of image capture and processing. Reality Scan allows for direct image capture within the application, whereas Reality Capture requires the uploading of separate photos. Additionally, Reality Capture offers additional features, including the ability to download and edit videos, as well as generate independent photos. Notably, Reality Scan is a specific type of 3D scanning technology that focuses on capturing surface geometry data, whereas Reality Capture is a broader term that encompasses the process of capturing and creating detailed 3D models using various technologies and methods. To facilitate a comparative analysis, multiple scans were performed using both software and various methods.

- The first model was made by the round method (Figs. 5 and 6)
- The second model was made using the spiral method (Fig. 7 and Fig. 8)
- The third model was made by a method where photos were taken randomly (Fig. 9 and Fig. 10)

This allows a clear comparison of scanning methods and their performance.

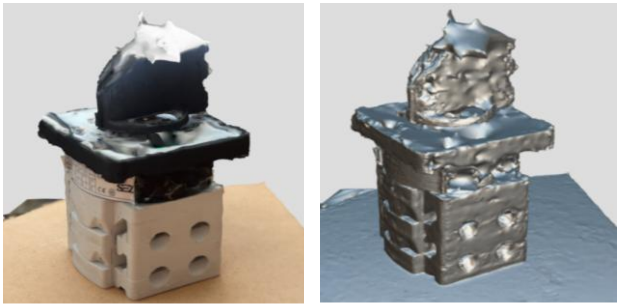

Figure 5. Reality Scan - circular scanning

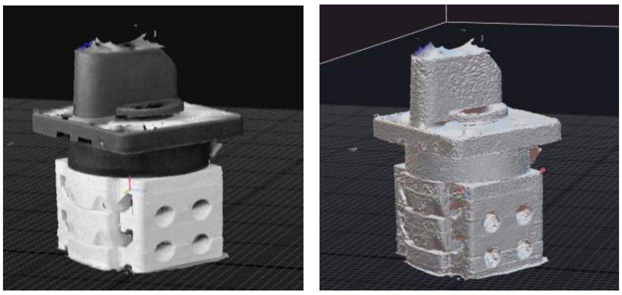

Figure 6. Reality Capture - circular scanning

During the circular scanning process, a total of 92 sequential images were captured around the object's circumference. The scanning protocol allows for a minimum of 24 images and a maximum of 256 images. However, the obtained results were affected by several factors, including the unevenness of the object's surface, which is a visible error. This error was also attributed to the scanning methodology employed, inadequate lighting, the limited number of shots, and the symmetrical shape of the object. Furthermore, the shiny surface of the object introduced an additional error during software interpretation, compromising the accuracy of the reconstructed model.

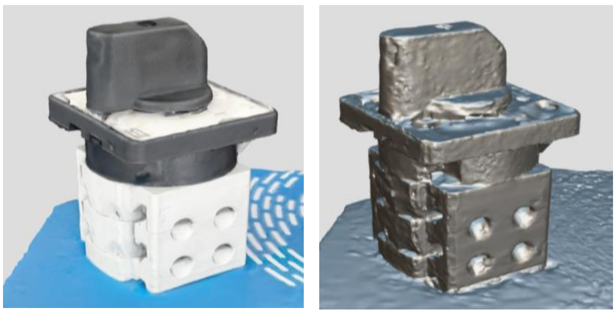

Figure 7. Reality scan – spiral scanning

The spiral scanning method yielded a more accurate result compared to the circular method, yet we still encountered challenges related to the glossy surface and the symmetrical shape of the object. The reflective surface continued to pose difficulties during image interpretation, and the object's symmetrical nature led to potential issues with feature extraction and model reconstruction.

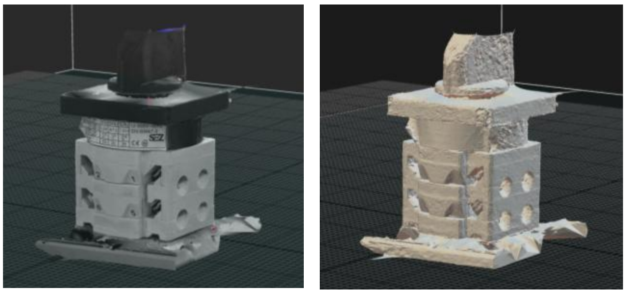

Figure 8. Reality Capture - spiral scanning

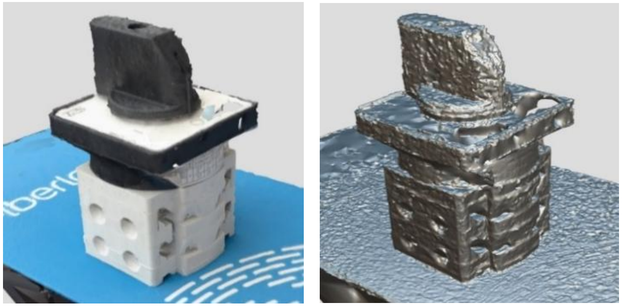

Figure 9. Reality scan – random scanning

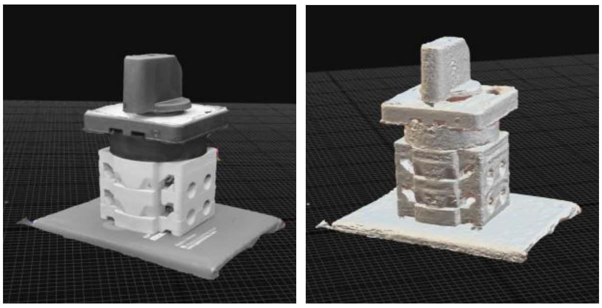

Figure 10. Reality Capture – random scanning

We attempted to capture a series of random images, and surprisingly, the reconstruction software was found to be less sensitive to precise trajectory adherence. Instead, it was observed that the key to obtaining a high-quality reconstruction was to minimize the repetition of image capture positions, rather than strictly following predetermined trajectories.

3.2 3D Scanning with Depth Sensors

3DMakerpro Seal Lite scanner was used for 3D scanning with depth sensors. To increase the quality of scanning, a two-axis rotary table 3DMakerproMulti-axis Turntable (Fig. 11) was also used for scanning models from multiple angles. Moreover, the scanner uses structured light encoded with shorter wavelength blue light to project refined patterns, capturing even the smallest details, textures and edges in high-resolution 3D models. Using JM studio scanning software it was possible to follow and control all steps of creating models. For generating 3D model, scanner made 998 images. As a result, desirable outcomes were attained (Fig. 12).

During the scanning process, the impact of the shiny surface and part symmetry on the resultant data was mitigated. The software's adaptive algorithm ensured that sufficient photometric details were captured to generate a high-fidelity 3D model. The combination of the 3DMakerproMulti-axis Turntable's systematic and symmetrical rotation, along with the securely fixed part and the scanner, facilitated the acquisition of accurate and detailed data, resulting in a faithful reproduction of the model.

Figure 11. 3DMakerproMulti-axis Turntable

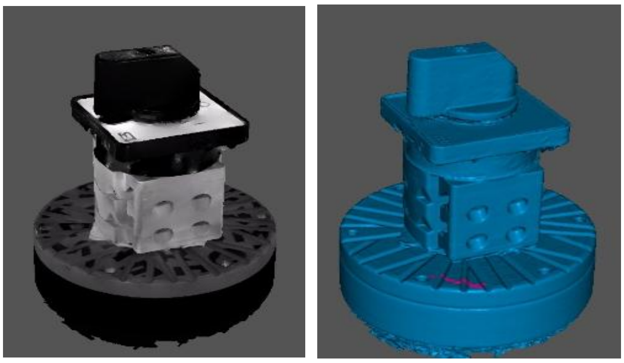

Figure 12. 3D scanning with a scanner 3DMakerpro Seal Lite

4 DISCUSSION

To examine and evaluate scanning methods and their resulting 3D models, the accuracy of the surfaces and details of these models was compared to their corresponding CAD models. Three different models were used for this comparison: (1) the optimal model generated by the Reality Scan software, (2) the optimal model generated by the Reality Capture software, and (3) a model created using a scanner. ZEISS INSPECT was selected as the comparison software. This software enabled the alignment of the scanned models with the CAD models, facilitating their connection (Fig. 13).

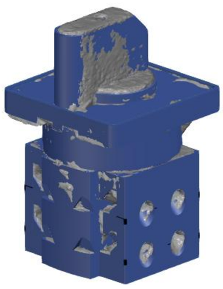

Figure 13. Alignment of the scanned models with the CAD models

Subsequently, ZEISS INSPECT allows for an inspection of the mesh model against the CAD model, where a color map is displayed, with each color indicating surface deviations. The maximum allowable distance (deviation) was set to 5 mm. In these color models, red areas indicate an excess of material, while blue areas signify a material deficit (Figs. 14, 15 and 16).

Comparison using this software is only approximate.
Inaccuracies may be caused:

- mesh fineness
- estimated scale adjustment
- algorithm that uses software to compare two mesh objects.

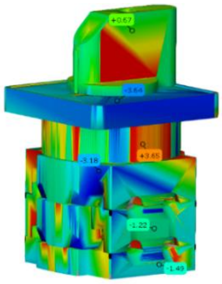

Figure 14. Comparison CAD and Reality Capture models

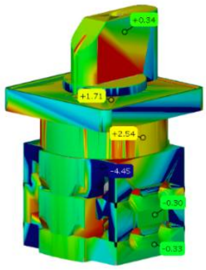

Figure 15. Comparison CAD and 3DMakerPro models

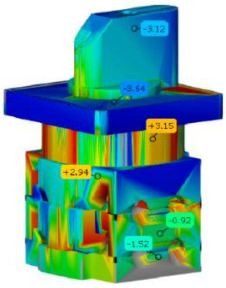

Figure 16. Comparison CAD and Reality Scan models

Under ideal conditions, comparing CAD models with scanned models should yield a result of zero, indicating an ideal surface without excess or deficiency of material. However, the scanning process is influenced by various factors such as lighting conditions, part size, surface characteristics of the part, the surface on which the part is placed, and object symmetry. Consequently, the figures illustrate the surface inaccuracies of the scanned models. Tab.4 compares the cumulative values where there is a deficiency of material and where there is an excess of material. The mean value of surface inaccuracy errors was also calculated by comparing the scanned models with the CAD models. For numerical comparison on the largest planes, specific points were selected in identical locations to indicate the error in millimeters.

$$\overline{x} = \frac{|x_1|+|x_2|+|x_n|}{n} \qquad (1)$$

Table. 4 Comparative values from each software

	Deficiency of material	Excess of material	Arithmetic mean
Reality Scan	6.09 mm	-9.2 mm	|2.54| mm
Reality Capture	4.32 mm	-9.53 mm	|2.31| mm
Scaner 3DMakerpro	4.59 mm	-5.1 mm	|1.61| mm

The models were also compared using Autodesk Inventor, where several dimensions considered critical for accuracy were determined. The exact dimensions are provided for comparison in the accompanying drawing (Fig. 17). For this comparison, the model scanned by the 3D scanner and made in Reality Capture were chosen due to its smaller discrepancies observed in previous software comparisons.

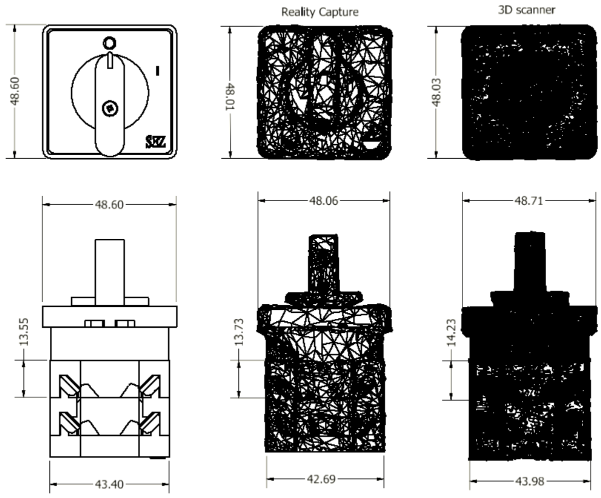

Figure 17. Accompanying drawing

Table. 5 Dimensions measured along each axis

	X axis	Y axis	Z axis
CAD	43.4 mm	48.6 mm	13.55 mm
Reality Capture	42.69 mm	48.01 mm	13.73 mm
Scanner 3DMakerpro	43.98 mm	48.03 mm	14.23 mm

Table 5 allows for a comparison of the dimensions measured along each axis across the three different methods. It highlights discrepancies between the models produced by Reality Capture and the 3D scanner compared to the CAD reference model. The Scanner 3DMakerpro model shows a slightly better overall accuracy in the X and Y dimensions. However, the Reality Capture model is more accurate in the Z dimension. Given the smaller deviations in the X and Y axes, which are typically more critical for overall fitting and assembly, Scanner 3DMakerpro could be considered more accurate overall.
When evaluating the quality of scanned objects, it is essential to consider not just the overall dimensions but the deviation of the measured data around the reference value. The table and accompanying drawing provide a visual and numerical comparison to assess the accuracy of different scanning methods against the CAD model. Based on all the obtained results, the best model was produced using the scanner. The highest average scanning quality was achieved with Reality Capture software, while the lowest quality was provided by Reality Scan. Also, when evaluating the resulting quality of scanned objects, it is important not only to consider the overall dimensions, but rather the dispersion of the measured data around the reference value. In this way, it is possible to more precisely determine the accuracy and consistency of the scanning methods compared to the CAD model.

5 CONCLUSIONS

In this study, object scanning was analyzed for its speed, convenience, and accessibility using two methods:

photogrammetry and 3D scanning with depth sensors. The objective was to evaluate several scanning techniques: circular scanning, spiral scanning, and random scanning, em
ploying photometry and two software applications for model generation: Reality Scan and Reality Capture. The findings indicated that scanning with a defined sequence produced superior results. Reality Capture software demonstrated better performance, generating more accurate scanned models. This conclusion was based on both visual assessments and numerical data comparing CAD and scanned models.

Regarding 3D scanning, the models produced were the most accurate, with enhanced texture details and component precision. The accuracy of scanned models was significantly influenced by the processing algorithm. Specifically, 3D scanner-produced models maintained a 1:1 object size ratio, whereas Reality Scan and Reality Capture software exhibited substantial size discrepancies.

In conclusion, for cost-free and high-quality user-level scanning, Reality Capture is the recommended software. For more detailed and professional scanning, a dedicated 3D scanner with appropriate software should be utilized. To enhance scanning quality, attention should be paid to the following factors:

- Lighting.
- Object texture and color.
- Surface on which the object is located.
- Object symmetry.
- Cameras and equipment.
- Software.

ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-23-0591, and by the projects VEGA 1/0700/24, KEGA 014TUKE-4/2023 granted by the Ministry of Education, Science, Research, and Sport of the Slovak Republic.

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