Comparative Analysis of Handheld Laser Scanner and Optical 3D Scanning Systems for Industrial Applications

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Abstract: This study explores the capabilities of the Scantech Simscan 42 laser scanner and the GOM ATOS Core 300 optical 3D scanner, using a tactile CMM as the reference standard. The focus was on evaluating the precision and reliability of these systems in measuring various geometrical characteristics such as diameter, distance, roundness, and flatness. The methodology included setting up and calibrating each scanning system, followed by capturing measurement data from a test object. The study aims to inform optimal usage of these systems in industrial applications like quality control and reverse engineering.

Keywords: *Industrial Metrology; Optical 3D scanner; Laser scanner; Measurement Accuracy*

1. Introduction

Modern industrial metrology requires highly precise and efficient measurement of object dimensions. Coordinate measuring machines (CMM) and optical surface scanning systems play a crucial role in this context. While CMM systems are widely used in industrial dimensional metrology, the digitization process can be very time-consuming when high data density is required. Optical systems, however, allow faster acquisition of dense point clouds, reducing labor needs and are often used in reverse engineering and quality control of free-form objects [1].

Tactile CMM machines measure an object's physical characteristics through contact, involving a probe attached to a moving z-axis that interacts with the workpiece placed on a platform worktable. These systems can be manually operated or computer-controlled, typically including a machine controller, a desktop computer, and specialized software. Optical 3D measurement systems, known as non-contact CMMs, use optical probes and dual cameras to simultaneously observe both the probe and the workpiece. This setup utilizes optical triangulation techniques to calculate dimensions, offering arm-free probing that significantly enhances productivity [2].

The primary function of a 3D scanner is to digitally replicate an object's shape and size by capturing its details without contact. In the context of the fourth industrial revolution, 3D scanners fulfill critical needs in digital manufacturing by developing dense data clouds from an object's surface using white or blue light. These scanners, equipped with sensors and cameras, capture multiple images for analysis by high-end software, which computes point coordinates across the visible area [3]. This process, also known as digitization, inspects an object's surface and reconstructs it in a virtual space using a network of points (xyz), forming a 3D graphical representation. The application of 3D scanning technologies has expanded more than tenfold recently [4].

3D scanning finds extensive application across various fields. In the manufacturing industry, it serves as a vital tool for reverse engineering, inspection, and quality control by comparing main part models with 3D models of manufactured parts. It is also used in tooling design, updating CAD files to reflect as-built tooling measurements, and tooling validation and inspection. In assembly and production, 3D scanning aids in virtual assembly, tool/robot path programming, and pre-machining part assessment.

Quality control applications include first inspection, part-to-CAD inspection, and supplier quality checks [4,5]. Additionally, 3D scanning is crucial in cultural heritage for archiving artifacts, creating virtual museums, educational resources, and documentation in case of loss or damage. In medical sciences, it is used for producing prostheses. Optical 3D scanners are also utilized in rapid prototyping, medical diagnostics, surgery planning, architecture, art, culture, archaeology, and paleontology, offering fast and confident production through their integration with rapid prototyping and additive technologies [6].
Measuring the 3D shape of shiny surfaces, such as aluminum alloy or titanium alloy turbine blades, poses significant challenges for optical metrology. Contact CMMs are typically used for such measurements as they are not sensitive to the optical properties of the part surface. However, their low measurement speed is a major drawback. Conversely, image-based optical non-contact 3D shape measurement techniques can measure very quickly, but their precision is affected by the optical properties of the part surface [7].
The most recent significant advancements in the field of 3D measurement systems have been summarized in Table 1. The cited literature highlights the diverse applications of 3D scanning technology across various industries, emphasizing its role in enhancing precision, efficiency, and quality control.

Table 1. *Review of previous research in the field of 3D measurement systems*

Source	Summary of key developments
[8]	The paper discusses the use of reverse engineering to create a digital model of face gear from a 3D point cloud, enabling precise reproduction of scanned objects for analysis and simulation. The process includes capturing a large number of 3D points, combining partial views, transforming measurements into a global coordinate system, and polygonization to create a mesh of nonoverlapping triangles
[9]	The study aimed to evaluate the reliability of 3D optical scanning for measuring foot and ankle volume compared to the figure-of-eight method in a preclinical setting. The touchless 3D optical scanning method is recommended for quantifying ankle edema in a clinical setting due to its accuracy, lack of patient cooperation requirement, and reduced risk of infection.
[10]	The paper presents a method for enhanced polymer spur gear inspection based on 3D optical metrology, offering a holistic measurement approach with significant advantages over tactile methods. The research validates the method by comparing results with a coordinate-measuring machine, showing good agreement between the optical and tactile methods.
[11]	The paper presents a measurement solution for face gears using 3D optical scanning, addressing the limitations of accuracy and related measurement solutions in complex gear geometry. The study validates the proposed method through a measurement experiment and loaded tooth contact analysis
[12]	The paper explores the potential of optical scanning technologies, like structured light scanners, for 3D printing medical devices in radiation oncology, focusing on their accuracy and practicality in clinical settings. Optical scanning has advantages like higher spatial resolution and textural information, showing promise for 3D printing applications in radiation oncology
[13]	The research paper focuses on developing a dynamic scanning system for large aerospace parts to enhance measurement efficiency and point cloud coverage. he system improves measurement efficiency by over 75% and enhances point cloud coverage by 18% for large aerospace components with complex surfaces.
[14]	The paper focuses on evaluating the dimensional and shape accuracy of components produced through Material Extrusion (MEX) using a cost-effective 3D scanning system, proving its reliability and repeatability for quality control.

[15]	The paper reviews the significance of 3D scanning in the furniture industry, emphasizing applications like dimensional inspection, virtual analysis, and prototype manufacturing. 3D scanning aids in preserving, analyzing, and reconstructing antique furniture pieces, enabling replication of existing products even without complete technical documentation.

Laser scanning and structured light sensors are two well-established non-contact optical measurement techniques. Both techniques are based on geometric triangulation principles to determine actual object point coordinates, ensuring high measurement accuracy. The difference lies in how the data for triangulation is obtained, either through a single laser beam spot or a unique surface phase map produced via phase shifting. Laser scanner systems (Fig. 1) use static detection units to record projected laser beams reflected off the object's surface, and the object's coordinates are calculated by applying triangulation techniques [15]. Data collection involves converting angular and range measurements into a Cartesian coordinate system, detailing the object's surface in immense detail. [16]

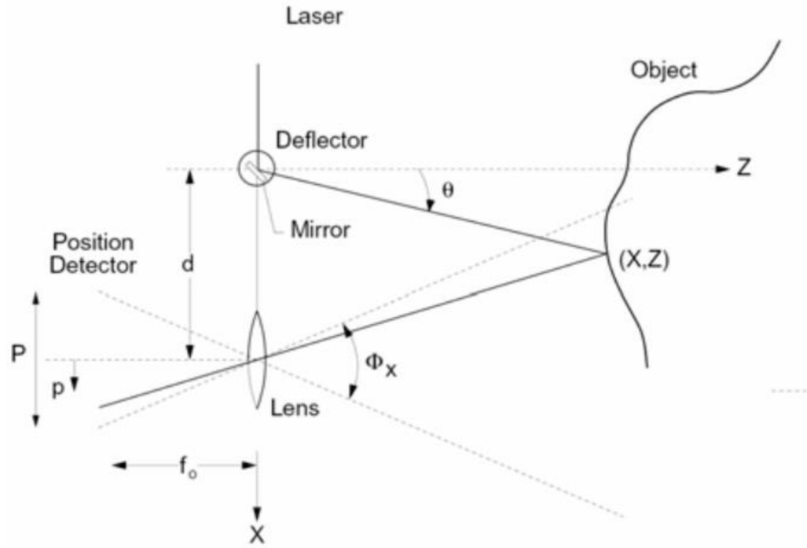

Figure 1. *Principle of laser scanner systems*

Structured light sensors use visible non-coherent light sources for object point coding, projecting light onto the entire camera field of view, allowing for the measurement of millions of points in a single view. These sensors (Fig. 2), now commonly equipped with two cameras, provide an over-determined mathematical triangulation model, enhancing measurement accuracy and reliability [15,16].

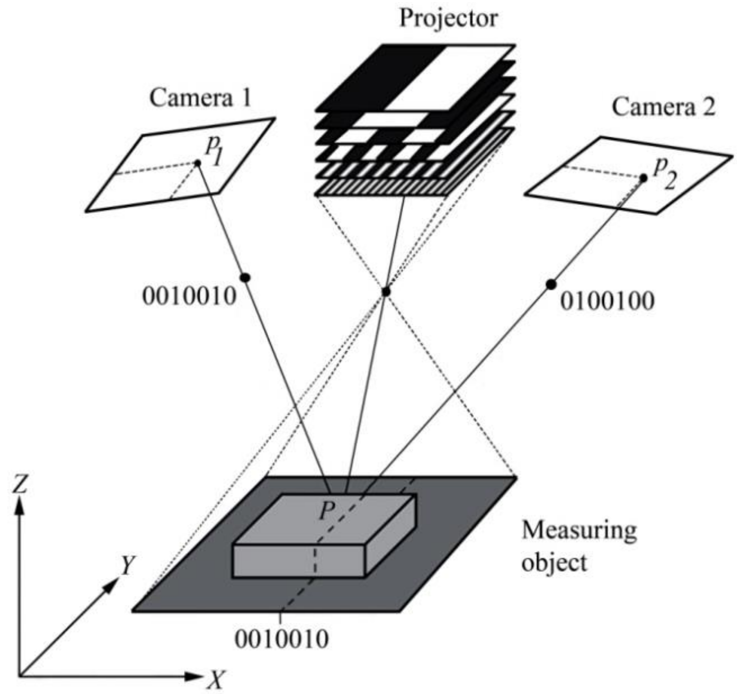

***Figure 2.** Principle of optical 3D measurement systems [10]*

In this study, optical 3D measurement systems and laser measurement systems will be invesigated, comparing their results with those obtained from tactile CMMs, which are considered the most accurate. Aim of this paper is to understand precision, efficiency, and applicability of these systems by evaluating them across different scenarios. The results of this research will provide valuable insights into the advantages and limitations of each system, guiding their optimal use in industrial applications and contributing to advancements in metrological practices.

2. Materials and methods

The research process involved a systematic approach to measure and compare the accuracy of a measurement object using different systems (Fig 3.). Initially, the measurement object was prepared for analysis. This object was first measured using a Coordinate Measuring Machine (CMM) system to obtain reference data, which served as the benchmark for subsequent measurements. The next step involved calibrating both the optical 3D measurement system and the 3D laser measurement system to ensure their accuracy.

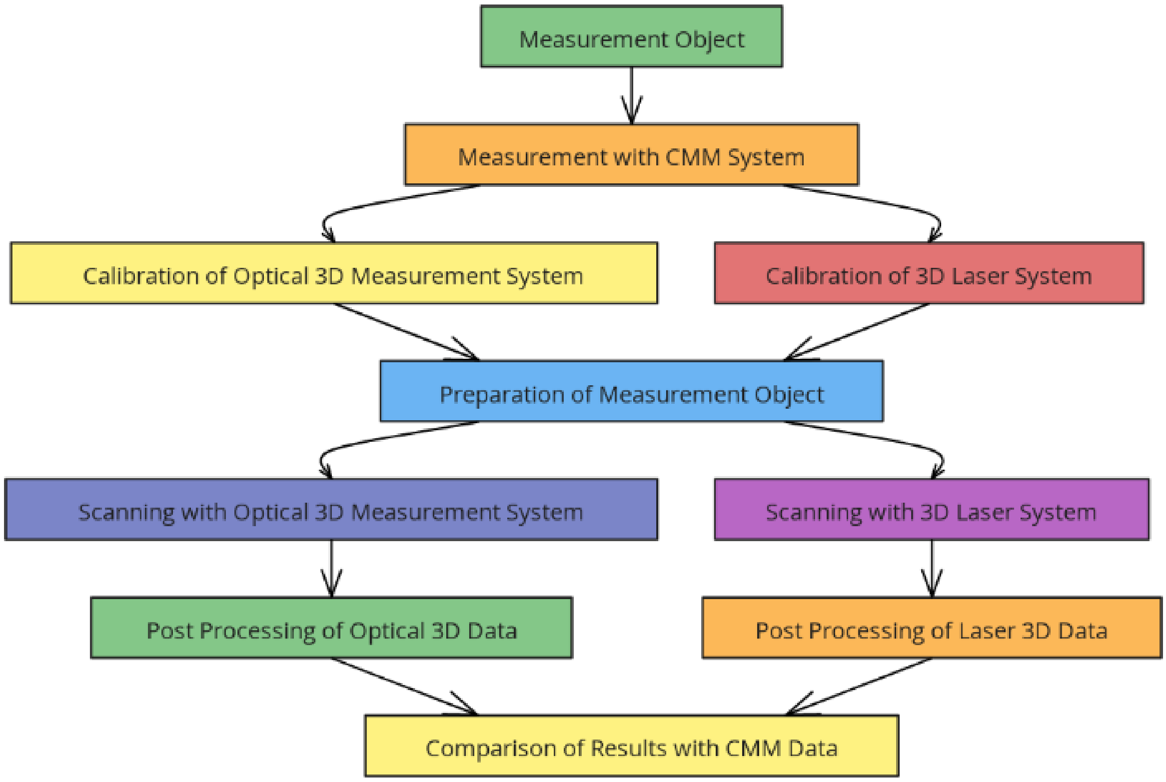

Figure 3. *Flowchart of the research process [Authors]*

After calibration, the measurement object underwent further preparation for scanning. The object was then scanned using both the optical 3D measurement system and the 3D laser measurement system. The data obtained from these scans were processed separately. This post-processing phase included editing the mesh and performing the measurement procedure for both the optical and laser 3D data. Finally, the results from the optical 3D and laser 3D measurements were compared with the reference data obtained from the CMM system. This comparison allowed for an evaluation of the accuracy and reliability of the different measurement systems, ensuring that the measurements were valid and consistent.
In this study, the ZEISS CONTURA G2 CMM machine (Oberkochen, Germany) was utilized to measure the dimensions of reference objects (Fig. 4). The ZEISS CONTURA G2 is a high-precision coordinate measuring machine equipped with the VAST XT probe head. It offers a length measurement accuracy of 1.5 + L/350 µm and operates effectively within a temperature range of 18-22°C. The machine supports a measurement volume of 700 x 1000 x 600 mm, making it suitable for a variety of industrial applications requiring precise dimensional analysis. The measurement process involved using the machine's advanced sensor technologies, including the VAST navigator and HTG options, to ensure accuracy despite temperature variations. These reference measurements were essential for comparing the performance of optical and laser measurement systems against the tactile CMM, recognized for its superior accuracy in industrial metrology.

Figure 4. *CMM machine ZEISS CONTURA G2*

The ATOS Core 300 3D scanner (Fig. 5) from GOM (Braunschweig, Germany) was employed to measure the dimensions of the test objects. This device was chosen for its reputed high resolution (0.12 mm) and precision in capturing detailed geometries, which is essential for accurate reverse engineering and quality control applications. According to the manufacturer, the ATOS Core 300 utilizes structured blue light technology to produce high-quality 3D polygon meshes, claiming minimal measurement deviations. This advanced scanning system is designed to handle small to medium-sized components effectively, providing detailed and precise measurements that support a wide range of industrial applications, including automated inspection, rapid prototyping, and comprehensive quality control assessments.

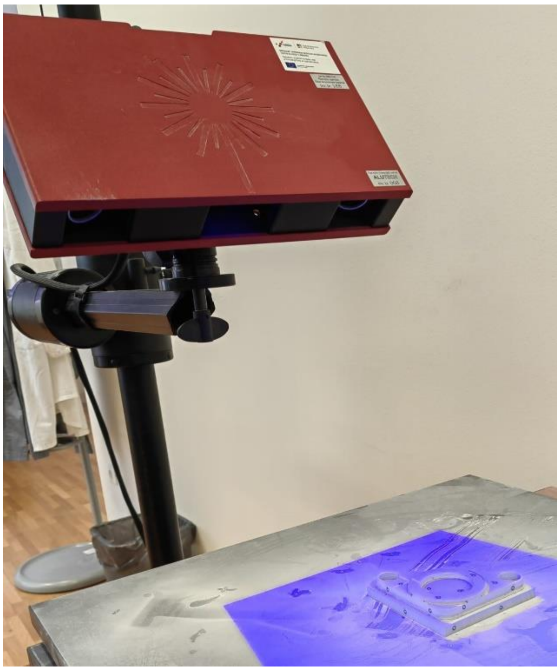

Figure 5. *Optical 3D scanner GOM ATOS core 300*

For laser scanning, the Simscan 42 (Fig. 6) laser scanner from Scantech (Hangzhou, China) was utilized. This device was chosen for its compact size, portability, and high precision, making it suitable for scanning in confined spaces. According to the manufacturer, the Simscan 42 employs advanced blue laser technology, capable of capturing up to 2.8 million measurements per second with an accuracy of up to 0.020 mm. Its robust design and versatility facilitated efficient and detailed data acquisition, essential for comprehensive quality control and reverse engineering applications.

Figure 6. *Laser scanner Scantech Simscan 42*

After scanning with both devices, the next step involved post-processing and measurement using GOM Inspect Professional software (Braunschweig, Germany). This software was employed for detailed analysis and inspection of the scanned data. GOM Inspect Professional is a comprehensive metrology software offering tools for quality control, inspection planning, and reverse engineering. It supports the evaluation of 3D point clouds, meshes, and CAD data, providing capabilities for alignment, deviation analysis, and reporting. The software's advanced features ensure accurate assessment and visualization of measurement results, facilitating efficient post-processing of data from both the Scantech Simscan 42 and the GOM ATOS Core 300 scanners.
This study encompassed various geometrical characteristics to gain a comprehensive understanding of the measurement capabilities of these devices for industrial applications. The measured dimensions included diameter, distance, roundness, concentricity, flatness, parallelism, perpendicularity, hole depth, and angle. The measurement object, designed specifically for this research, was a steel component fabricated using CNC machining. This object, shown in Figure 7, features the necessary geometries to facilitate detailed analysis, ensuring that each measurement system's capabilities could be thoroughly assessed across all the specified characteristics.

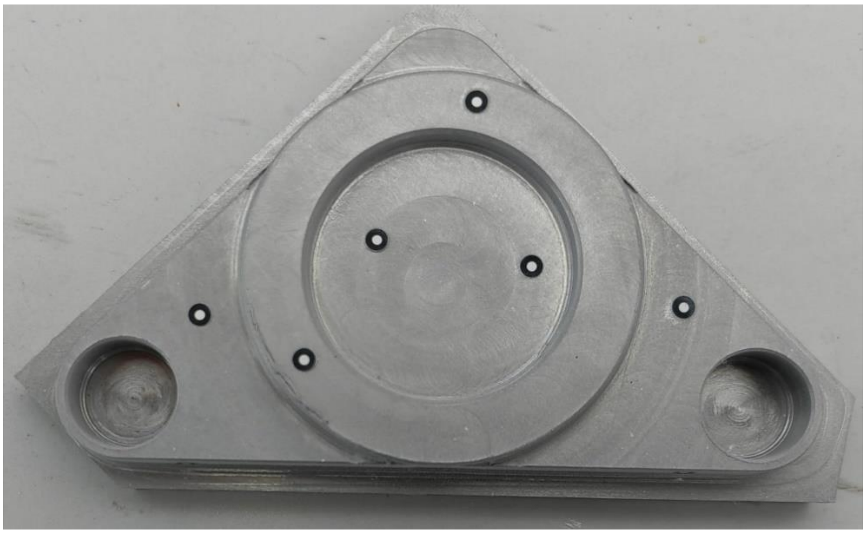

Figure 7. *Mesurement object*

3. Results and discussion

The results of the measurements conducted with the tactile CMM, laser scanner, and optical 3D scanner are summarized in Table 1. This comparison includes various geometrical characteristics such as diameter, distance, roundness, concentricity, flatness, parallelism, verticality, hole depth, and angle.

Table 1. *The result of measurements*

Geometrical characteristic	CMM	Laser	Optical 3D scanner
Diameter	15.882	15.730	15.891
Distance	93.125	93.142	93.128
Roundness	0.163	0.20	0.17
Concentricity	0.10	0.05	0.09
Flatness	0.035	0.07	0.04
Parallelism	0.025	0.3	0.08
Verticality	4.25	1.05	1.17
Hole depth	7.003	6.89	7.03
Angle	45.42	45.18	45.28

The following diagrams illustrate the deviations of the laser and optical 3D scanner measurements from the CMM reference values for various geometrical characteristics (Fig. 8). The characteristics examined in this study include Diameter, Distance, Roundness, Concentricity, Flatness, Parallelism, Verticality, Hole Depth, and Angle. Each diagram represents the deviation of a specific characteristic, where the CMM measurements are considered as the baseline (zero deviation).

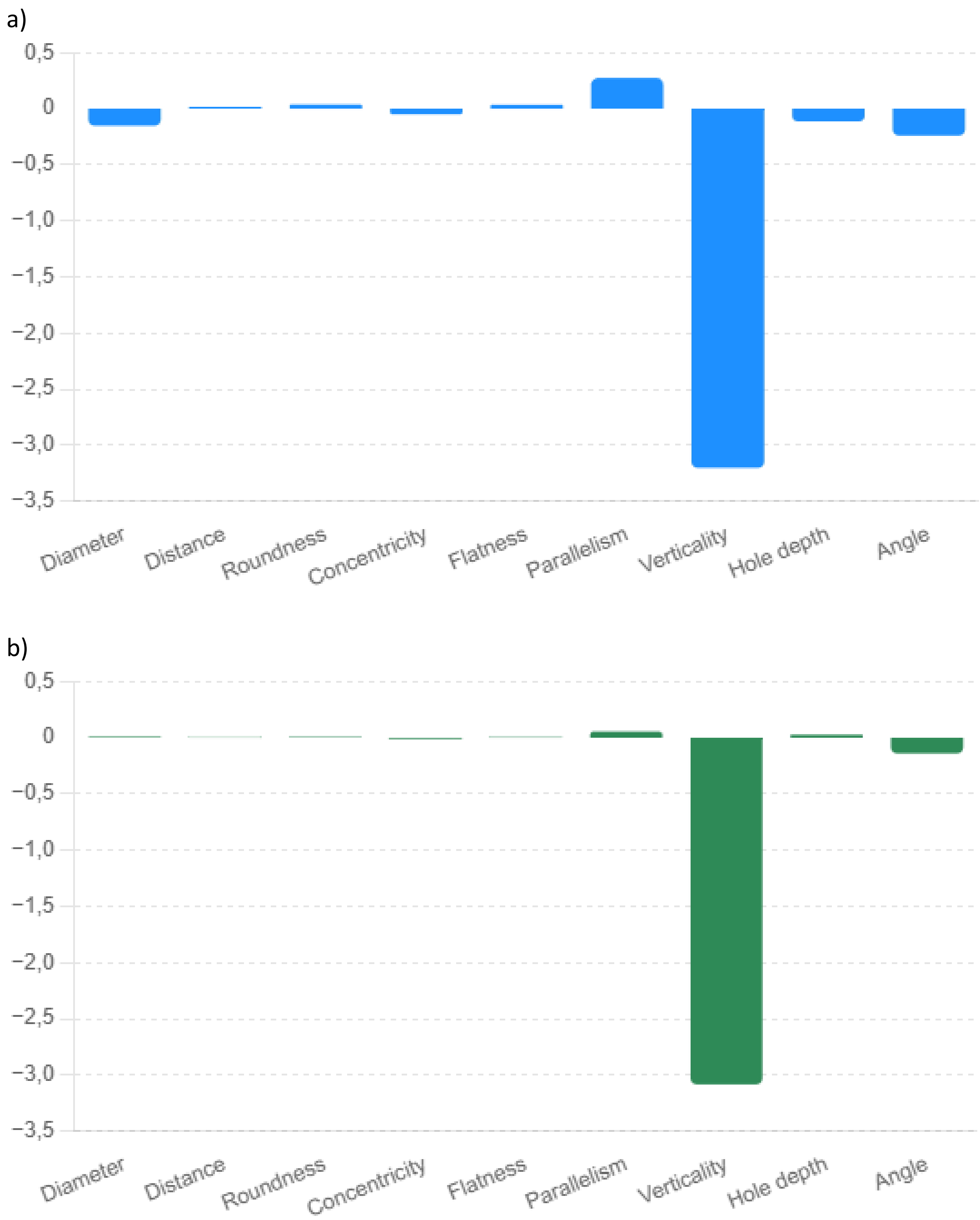

Figure 8. *Deviations from the CMM reference values: a) Laser scanner; b) Optical 3D scanner*

The analysis of deviations from the CMM reference values reveals specific differences between the optical 3D scanner and the laser system, with the optical 3D scanner generally showing smaller deviations. For diameter measurements, the optical scanner recorded a deviation of only 0.009 mm, compared to 0.152 mm for the laser system, indicating higher precision for the optical system. Both systems displayed minimal deviation in distance measurements, with 0.003 mm for the optical scanner and 0.017 mm for the laser scanner, confirming the optical system's slightly better accuracy.

In terms of roundness, the optical 3D scanner showed a deviation of 0.007 mm from the CMM reference, compared to 0.037 mm for the laser system, further demonstrating its superior accuracy. Similarly, concentricity measurements indicate that the optical 3D scanner is more accurate, with 0.01 mm deviations from the CMM reference, whereas the laser system has 0.05 mm deviations.

The flatness measurement further reinforced the optical scanner's accuracy, as it deviated only by 0.005 mm, while the laser scanner showed a larger deviation of 0.035 mm. Parallelism measurements exhibited a notable deviation for the laser system (0.3 mm), whereas the optical 3D scanner deviated by 0.055 mm, suggesting the optical system's better performance in planar measurements.

Verticality results presented larger deviations in both systems, with the laser system deviating by 3.2 mm and the optical system by 3.08 mm. In hole depth measurements, the optical system showed better accuracy, with a deviation of 0.027 mm compared to the laser system's 0.113 mm deviation.
The angle measurements indicated that the optical 3D scanner provided a smaller deviation (0.14°) than the laser system (0.24°), showing better precision in angular measurements.
The optical 3D scanner demonstrates superior accuracy and precision compared to the laser measurement system. This is evidenced by the smaller deviations from the CMM reference values across most geometrical characteristics. Several factors contribute to the enhanced performance of the optical 3D scanner:

- Fixed Setup: Optical 3D scanners are typically used in a fixed setup, ensuring stability and reducing the potential for human error. This stability allows for consistent and repeatable measurements, minimizing deviations.
- Human Error: Handheld laser scanners rely on the operator's ability to maintain consistent movement and positioning during the scanning process. Any variation in speed, angle, or distance from the object can introduce significant errors and inconsistencies in the measurements.
- Stability Issues: Unlike fixed setups, handheld scanners are prone to instability. Even slight movements or vibrations can affect the accuracy of the scan, leading to larger deviations from the reference values. This instability is particularly problematic for measurements that require high precision, such as roundness, flatness, and parallelism.
- Alignment and Calibration: Ensuring proper alignment and calibration of handheld scanners is more challenging compared to fixed systems. Misalignment during scanning can cause significant errors, especially for complex geometrical characteristics that require precise measurement.

Several studies support the findings presented in this research. For example, the work by [18] confirms that optical 3D scanners, particularly when used in controlled setups, exhibit superior accuracy in comparison to handheld laser systems, especially in fine geometric details such as flatness and roundness. Similarly, [19] highlights the challenges handheld laser scanners face due to operator influence and instability, which can lead to larger deviations, as observed in this study. These references corroborate the performance differences noted between the optical and laser measurement systems in this research.

Despite the overall superior accuracy of the optical 3D scanner, significant deviations are observed in the measurements of certain geometrical characteristics, particularly those involving surface measurements. This discrepancy arises due to differences in the measurement procedures. Unlike the CMM, the optical 3D measurement system captures the entire surface of an object, leading to potential deviations if even a small part of the surface has inconsistencies. The comprehensive data acquisition by the optical 3D scanner, while generally advantageous, can introduce errors when localized surface irregularities are present. Additionally, the software used for these measurements dates back to 2016. Since then, there have been significant advancements in measurement software, improving data processing, error correction, and approximation algorithms. Future research should incorporate the use of modern software to leverage these advancements and further reduce measurement deviations.

4. Conclusion

The study compared measurements from the Scantech Simscan 42 laser scanner and the GOM ATOS Core 300 optical 3D scanner against reference data obtained from a tactile CMM. The GOM ATOS Core 300 demonstrated superior accuracy, showing minimal deviations across most geometrical characteristics, such as diameter, roundness, and flatness. It proved particularly effective in capturing fine details, making it suitable for comprehensive quality control and reverse engineering applications. Conversely, the Scantech Simscan 42 exhibited more variability, especially in diameter and flatness measurements, yet excelled in concentricity and verticality assessments. This variability is attributed to the manual operation of the laser scanner, which is sensitive to operator handling and environmental conditions. The laser scanner's compact and portable design, however, provides a unique advantage for scanning in confined or hard-to-reach areas.

These results highlight the importance of selecting the appropriate measurement system based on specific industrial needs. The optical 3D scanner's higher accuracy makes it ideal for applications requiring precise detail, while the laser scanner offers versatility and ease of use in more complex environments. Future improvements in scanning technology and software could further enhance the accuracy and reliability of these systems, broadening their application scope in industrial metrology.

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