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COMPARISON OF MODERN 3D MEASUREMENT METHODS FOR SPECIAL TASKS OF SHIPBUILDING INDUSTRY

Research presents modern technologies of 3D measurements in shipbuilding production parts. A special template of the keel detail was made for the research. Detailed measurements with a laser tracker, laser scanning, industrial photogrammetry, and handheld scanning are performed. Leica Absolute Tracker AT960-LR was used for Laser tracker measurements. Laser scanning was performed with Z+F Imager 5010. Nikon D2Xs photo camera was used for Industrial photogrammetry. Handheld scanner DPI-7 from DotProduct was also used for 3D measurements of the details. All collected data were imported into 3DReshaper software for comparison. The accuracy comparison for the specific equipment used in the study is performed. The recommendations for optimal equipment use and software products in this research are also included. The authors also present the assessment of the cost and time spent on the measurements.

Key words: 3D measurements, laser tracker, laser scanning, industrial photogrammetry, handheld scanning

Introduction

Determining 3D surface points on components is essential in current shipbuilding production. Nowadays digital twins of engineering objects are also important for shipbuilding [Hoffman et al., 2023]. In such applications photogrammetric and lidar-based technologies can be used to provide 3D detailed models of objects' surfaces [Martorelli et al., 2014; Burdziakowski & Tysiąc, 2019; Goldan & Kroon 2003]. Ship components can vary in size from a few to tens of meters in length. Modern technologies of three-dimensional measurements, in particular, enable the accurate and expeditious determination of surface point coordinates for objects within such a size range. Among the currently used techniques, such optical methods as laser scanning, handheld scanning, industrial photogrammetry, and laser tracker measurements are often used. The tendency of three-dimensional measurements is characterised by submillimeter-level accuracy, affordability, real-time or near real-time processing, and equipment portability. As existing methods undergo enhancements and new techniques emerge, it becomes crucial to engage in comparative analysis to identify the most optimal solution for specific tasks.

To evaluate modern three-dimensional measurement technologies in the shipbuilding industry, four optical methods were utilized: laser scanning, handheld scanning, industrial photogrammetry, and laser tracker measurements. A template detail of the ship's keel was specially made for the research (Fig. 1). It is 2.027 m long, 1.950 m wide, and 1.045 m high. The part of the detail is milled and includes the special pocket. The practical part of this research was conducted at the Ostseestaal factory in Stralsund, Germany [Brusak, 2018]. The material used in the study was completely collected and analysed by the article's authors.

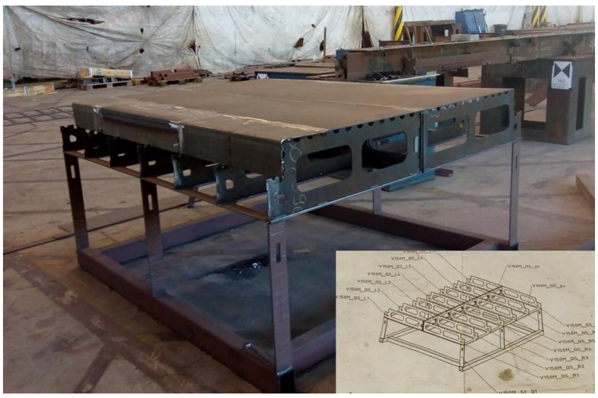

Fig. 1. An experimental template of the ship's cron beam was specially made for research

Various optical methods can be employed in engineering to construct 3D representations of natural objects. It is crucial to determine the most optimal research method from both an economic and engineering perspective. The primary concern from an engineering standpoint is ensuring measurement accuracy, which may need to be at a level of 0.1-0.3 mm. The economic aspect involves utilising cost-effective equipment, minimising work time, and reducing labour requirements. Considering these factors, comparing modern technologies of three-dimensional measurements represents a pertinent industrial challenge.

To date, some studies have already been performed in comparing optical measurement methods.

A laser tracker and laser scanner results are compared using experimental tests concerning the dimensional verification of cruise-ship modules [Maisano et al., 2022]. The authors concluded that the laser tracker dominates for metrological performance, but its considerable size seems to limit portability. Using the laser tracker also requires a certain degree of dexterity by the operator handling the target (SMR or T-Probe) and involves quite considerable set-up times. The laser scanner is particularly suitable when measuring complex features and when their full 3D reconstruction is needed. The most critical aspect of the instrument is the need to transfer and analyse (offline) the acquired data without providing the measurement results in real time.

There was a similar research [Ahmed et al., 2011], which compared point-cloud acquisition from laser-scanning and industrial photogrammetry. The following conclusions were reached: the selection between laser scanning and photogrammetry should be contingent upon specific project requirements. When cost considerations take precedence, photogrammetry may be the technology of choice for point cloud generation. Conversely, when issues related to training duration and expertise are pertinent, laser scanning technology appears to be the more suitable option [Ford et al., 2016]. Geometrical parameters were quantified using industrial photogrammetry and laser scanner technology, with data processing facilitated by MATLAB software [González-Jorge et al., 2012]. The acquired results were subjected to a comparative analysis with the manufacturer's original geometric specifications, taking into consideration the tolerance thresholds and uncertainty intervals stipulated by industry standards. The authors state that both methodologies demonstrated their metrological competence in performing the requisite measurements within the specified tolerances.

Concerning handheld scanners, Kersten et al., [2016] compare DotProduct DPI-7, Artec Spider, Mantis vision F5 Short rank, Kinect v1 and v2, Structure Sensor, and Google Tango. Observations were incorporated into the bundle block adjustment process, including data from three calibrated scales. This integration led to achieved accuracies ranging from 0.1 to 0.6 millimetres. The results for the DPI-7 handheld scanners are homogeneous for all systems and oscillate themselves in the case of the probing error PF from approx. 10mm. With the DPI-7 data, a problem registering single scans occurs as concatenated registration with stretched objects. Considering the acquired data, it is deductive that utilising the DotProduct DPI-7 is deemed suitable for task execution.

The primary objective of the research is to ascertain the suitability of four technologies of three-dimensional measurements for the modern shipbuilding industry. The study involves conducting the accuracy assessment of 3D point clouds generated by these methods and evaluating investment in time and finances for their implementation. Currently, no comparative analysis has been conducted encompassing laser tracker measurements, laser scanning, industrial photogrammetry, and Handheld Scanning within the context of the shipbuilding industry.

Research Methodology

Data used in research

The research employed four modern optical measurement methods: terrestrial laser scanning, handheld scanning, engineering photogrammetry, and laser tracker operation. The utilised equipment is depicted in Fig. 2 and comprehensively described in the subsections below. Laser Tracker Measurements were adopted as the baseline method since they exhibited the highest measurement accuracy and are widely accepted in the shipbuilding industry [Moniuk, 2012; Maisano et al., 2022].

Laser Tracker Measurements

The laser tracker is a mobile coordinate measurement device that operates on the principle of tracking a special reflector using a laser beam. The instrument measures the angle and distance to a spherical target. The measured parameters are used to determine the 3D coordinates of the centre of the spherical reflector in the laser tracker's coordinate system.

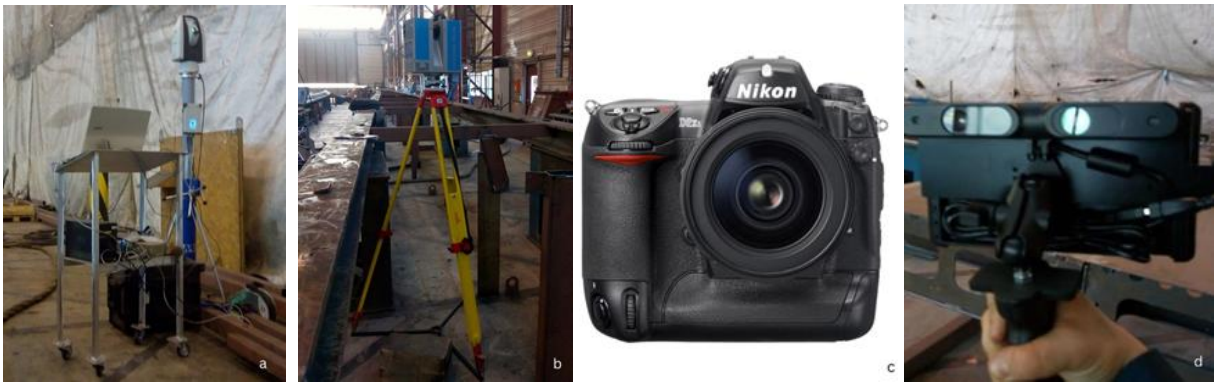

Fig. 2. Instruments used in the research: Leica Absolute Tracker AT960-LR (a), Z+F Imager 5010 (b), Nikon D2Xs photo camera (c), DPI-7 handheld scanner (d)

Trackers are used to monitor the geometric parameters of large-scale products such as aircraft, ships and railcars, automobiles, machine tools and presses, and large metal structures [Moniuk, 2012]. They can effectively control complex curved surfaces by comparing them to a CAD model. The unique ability to track the position of a spherical reflector in real time allows trackers to be efficiently used for assembling products, such as joining individual sections of a ship. The use of a laser tracker eliminates the need for the production of special measurement control templates.

This research shows the results of using Leica Absolute Tracker AT960-LR [Hexagon …, 2022]. AT960-LR is a laser tracking system that uses an interferometer-based ranging system to accurately determine the distance between the tracker and the target. The laser tracker enables 3D measurements up to 160 meters in diameter and a 6DoF measurement volume up to 40 meters in diameter, with the data collection speed up to 1000 points per second. There is a possibility to use a special reflector called Leica T-Probe. The mean squared error (MSE) for interferometer and angular accuracy is ± 0.4 μm + 0.3 μm/m, ± 15 μm + 6 μm/m respectively. The AT960-LR is equipped with an integrated MeteoStation that continuously monitors environmental parameters, such as temperature, pressure, and humidity.

Data collection and processing are performed using Leica Tracker Pilot software. The model construction of the adhesive angle of the ship in this study includes the tracker's orientation, measurements of the top and sides of the detail, and data exporting in .txt format. In the result, 1043 points of detail are measured. The further mesh model is built in 3DReshaper software.

Laser Scanning

Terrestrial Laser Scanning (TLS) is the technology of acquiring point data about an object's surface using a laser beam. The laser is mounted on a rotating base. The laser beam is scattered on the object's surface during scanning, and a laser scanner captures its reflection. The measurement results are a point cloud on the surface due to the reflected radiation from the object's surface. The point data creates a three-dimensional representation of the object's surface with high accuracy and detail [Abbas et al., 2017].

TLS involves capturing many high-density point clouds from various viewpoints to cover the entire area of interest. This method does not depend on the illumination of the object under investigation. The high productivity of laser scanning is characterised by obtaining a large volume of data quickly with sufficient accuracy to perform most engineering tasks.

The results of the operation Z+F Imager 5010 in this research are shown. Z+F Imager 5010 is a highly precise and reliable instrument for laser scanning at close and far distances. It can scan up from 0.3 to 187 m with up to 1 million pixels/sec. The extended field-of-view of this device is wide – with 320° vertically and 360° horizontally. Four scans were performed using TLS data in "high" resolution and "normal" quality to create the model. Processing is done in software products Scantra and Z+F Laser-Control. The point cloud was exported in .pts format (Fig. 3) for further processing in 3DReshaper software.

Fig. 3. The point cloud data based on TLS data

Industrial Photogrammetry

Industrial photogrammetry, related much to close-range photogrammetry, is based on general principles of classical photogrammetry [Ackermann et al., 2008]. Calculation of the objects' 3D coordinates includes two main steps. Firstly, finding the images` orientation parameters in a standard 3D coordinate frame is necessary. Second, the subsequent generation of a dense point cloud is performed.

Luhmann T. [2010] divides the current industrial photogrammetry into two types, such as off-line and on-line systems. In this research, we used an off-line system that allows the highest precision and accuracy levels. The precision of image point measurement can be as high as 1/50 of a pixel, yielding typical measurement precision on the object in the range of 1:100,000 to 1:200,000, the former corresponding to 0.1 mm for an object of 10 m in size. The absolute accuracy of length measurements is generally 2–3 times less [Rieke-Zapp et al., 2009].

This research shows the results of the using camera Nikon D2Xs. Integrating a 12.4 megapixel CMOS image sensor allows making up to five frames per second in continuous shooting mode. Work with an 11-area autofocus system produces JPEG or RAW images. The Nikon D2Xs helped to register such parameters for measuring as ISO 300, f-number – f 8.0, and flash sync 1:250. The ISO parameter regulates the level of cameras' sensitivity to available light. It is possible to transmit data wirelessly from the Nikon D2Xs to a computer with Camera Control Pro software using the Wireless Transmitter WT-2/2A during measurements.

In this research, AICON`s scale bars and special marks are used. The use of AICON`s scale bars and special marks is necessary for the precision results and the automatic calculations in the software products. The special marks are 8-bit coded. The calibration of the camera and special scale bars was made with a special horizontal comparator. In summary, the Nikon D2Xs camera and the calibrated scale bars suit precise photo-based scanning.

Nearly 300 photos were taken for research. The focal length is 24.188 mm for this camera. The MSE of the location equals 1.8 mm or 0.054 pix. The appearance of a dense point cloud is shown in Fig. 4. The data filtration is done manually. The results are exported in ASTM E57 format. The mesh model generation is made further in 3DReshaper software.

Fig. 4. Generated dense point cloud based on industrial photogrammetry results.

Handheld Scanning

Handheld scanners usually include a projector and measurement units. The measuring principle consists of two stages. Firstly, an infrared projector projects a pseudo-random pattern on the object. Secondly, this pattern and the shape changes are measured with NIR (Near-InfraRed) and RGB (Red, Green, Blue) cameras. The point cloud is converted from the range images. The coordinates are compensated to gravity using the tablet's internal accelerometer and gyroscope sensors [Jahraus et al., 2015].

The DPI-7 equipment consists of an android table computer with handle attachment, a license of DotProduct Phi.3D software, a 3D sensor made up of a near infra-red (NIR) projector, a NIR camera and an RGB colour camera, 3 USB to micro USB connectors for connecting the camera to the tablet.

Jahraus et al. (2015) check the work of the DPI-7 with this sensor and state that the errors in the depth dimension of the scanner are proportional to the square of the depth. The most potent part of the DotProducts' handheld equipment is the Phi.3D software on the tablet, which allows for intelligently registering and processing detailed point clouds on the fly [Ahern and Spring, 2015]. The specially used ICP algorithm for six degrees of freedom requires a procedure to find the closest point on a geometric entity to a given point. This algorithm always converges monotonically to the nearest local minimum of a mean-square distance metric, and the convergence rate is rapid during the first few iterations. The registration is optimised by automotive eliminations of incorrect points. During the measuring process, real-time feedback on the tablet at Phi.3D software is also a crucial advantage.

The measuring range of the DPI-7 scanner is between 0.6 m and 3.3 m. The instrument's weight is less than 1 kg, the dimensions are 20×24×6 cm^3. The DPI-7 is satisfactory equipment for the small projects of indoor scanning. Detailed measurements were made walking through the area around with the range of 1.5m. The colour point cloud was registered in a few minutes on the tablet in the field. The results of the measurements (Fig. 5) were exported in .ptx- format.

Fig. 5. The result of the scanning with the DPI-7 from DotProduct

Data Comparison and Results

Best-fit data comparison

All collected data were imported into 3DReshaper software. The mesh model of the point cloud was made for each case of optical and laser measurements. The best fit and 3-2-1 Registration functions are used for the accuracy analysis. The laser tracker measurements are chosen as the basis for comparison.

The laser tracker data mesh model includes 1,043 points and 1,967 triangles. The mesh model of the hand-held scanner consists of 9,564 points and 18,857 triangles after filtering. In the comparison, it was found that 80.4% of the surfaces of the mesh models are less than ± 0.003 m. The maximum differences are +0.015 and -0.019 m.

The mesh model based on the laser scanning data includes 10,646 points and 21,022 triangles. In the result of the comparison, it was found that 87% of the surfaces of the mesh models are less than ± 0.0015 m. The maximum differences are +0.007 and -0.009 m. The upper part of the sample part has better results on that side.

Table 1 shows the results of the best-fit comparisons of different methods with laser tracker data.

Table 1

The results of the best-fit comparisons of different methods with laser tracker data

Method (equipment) that compares with the laser tracker's data		Laser scanning (Z+F Imager 5016)	Photo-based scanning (Nikon D2Xs + Agisoft Photo-Scan)	Hand-held scanning (DPI-7)
The percentage of the area with diffe-rences less than	1mm	80%	60%	40%
	2mm	89%	80%	60%
	3mm	96%	93%	80%
Max. positive difference, [mm]		+7	+16	+15
Max. negative difference, [mm]		-9	-21	-19
Defected data		Convexity on the smaller side	All points of the smaller side	-
Improving the data		Smoothing	Filtering	-

The mesh model based on the industrial photogrammetry data includes 16,297 points and 31,953 triangles after the filtering. In the comparison, it was found that 93% of the surfaces of the mesh models are less than ± 0.003 m. The maximum differences are +0.016 and -0.021 m.

Defected data

After the measurements, it turned out that some data were distorted. This is due to the polished metal, which has additional reflective properties. The laser and photo-based scanning characterised the defective data. The convexity on the smaller side is related to the high reflection of the mark in that place. Based on the industrial photogrammetric data, all of the points on the smaller side are of unsatisfactory quality. It is related to the need for more photos of the small side.

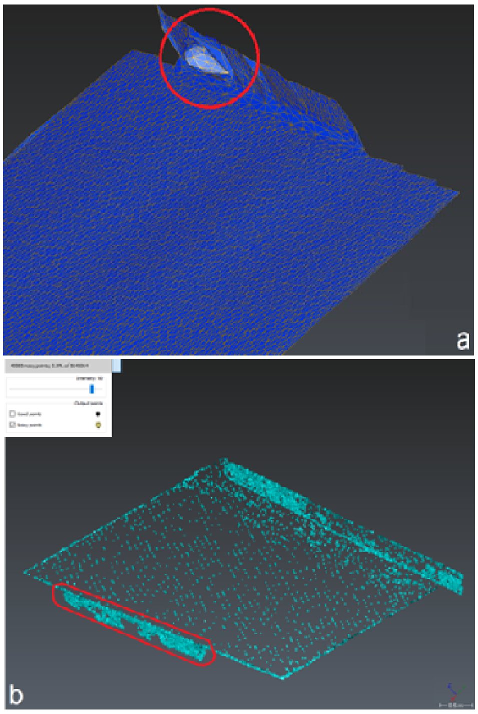

Fig. 6(a,b). Defected data: convexity on the side for the laser scanning (a), smaller side for the photo-based scanning

Measurement Time Comparison

The time needed for measurements, processing and getting point cloud data is an important parameter. In this case, the minimum time for measuring the simple analogue of the adhesive angle of the sheep is demonstrated if the user is only one and familiar with the equipment. The fastest method is the hand-held scanning (20 min). It needs 10 minutes to connect the DPI-7 and switch on the Phi.3D, 5 minutes for measuring, including the preheating time for the sensor and 5 minutes for saving and exporting the point cloud.

The work with laser scanner Z+F Imager 5016 and the Z+F Laser Control on the laptop in the field needs 15 minutes for connecting the equipment and fixing special marks in the hall and 30 minutes for measurements (4 stations, 6 minutes per station and installation at the station) with high accuracy and standard quality and 5 minutes for the data export. If it is essential to change the coordinate system of the scans to the coordinate system in the hall, the Total Station can be used. It needs nearly 20 minutes of measurements and 20 minutes more for exporting and recalculating the point cloud in Z+F Laser Control. Summing up, it needs 50 minutes for the laser scanner data and 40 minutes more for changing the coordinate system.

The laser tracker measurements with the AT960 need 20-30 minutes for the hardware connection of the system and preheating time for the AIFM, 10 minutes for the field check and positioning to the hall coordinate system, 15 minutes for the dynamic measurements (1,000 points with interval 5cm) with SMR and T-probe and 5 minutes for the export of the data. So, the process includes nearly 50-60 minutes of working time.

The most significant amount of time taken for the industrial photogrammetry (6.5 hours): 15 minutes for the fixing of the special photogrammetric marks, 40 minutes for taking 300 photos, 10 minutes for exporting, 30 minutes for the photos alignment and 5 hours for the building a dense point cloud in Agisoft Photoscan.

Table 2

Working time and equipment price used in the research

Method and equipment		Laser tracker (Leica AT960LR + T-probe + Spatial Analyzer)	Laser scanning (Z+F Imager 5016)	Photo-based scanning (Nikon D2Xs + Agisoft Photoscan)	Hand-held scanning (DPI-7)
Time, [min.]	preparation	30-40	15	15	10
	measurements	15	30	40	5
	export and processing	5	5	330	5
	sum	50-60	50	385	20
The approximate price for the equipment [$]		250, 000	85, 000	5, 000	5, 000

Equipment costs

The price of the equipment used in the research varies considerably. The most expensive equipment is one for laser tracker measurements. Leica Absolute Tracker AT960-LR with the special tripod, Spatial Analyzer license, and T-probe cost nearly 250,000 $. The price for the Laserscanner Z+F Imager 5016, Z+F LaserControl, and Scantra software are near 85,000 $. The handheld scanner DPI-7 with Phi.3D software and Camera Nikon D2Xs with the Agisoft Photoscan are much cheaper. The equipment for the handheld scanning and for the industrial photogrammetry cost near 5, 000 $ per measuring set.

Prospects for Further Research

Further research has several key aspects for the improvement and development of 3D measurement methods in the shipbuilding industry.

Accuracy and reliability of measurement methods: One of the important areas is the search for ways to increase the accuracy and reliability of modern measurement methods. This may include improvements in data processing algorithms, technical support, and the development of new equipment calibration methods.

Expanding the scope: Research may consider expanding the scope of 3D measurement techniques. For example, adapting them to control the deformations of other types of structures or developing new techniques and methods to provide measurements at greater distances with higher accuracy.

Improvements in data collection and processing technologies: Additional developments in software for data collection, analysis, and visualization can greatly facilitate the measurement process. The integration of artificial intelligence and machine learning can also help automate data processing and improve the accuracy of results.

Optimization of time and resources: An important aspect is the optimization of the time required for measurements and the efficient use of resources. The development of more effective methods of preparing equipment for work, shortening the measurement process, and accelerating the processing results will contribute to greater productivity.

Standardization and integration with other technologies: The development of standards for 3D measurement methods in the shipbuilding industry and their integration with other technologies creates greater opportunities for improving all work processes and interactions between them in this industry.

These areas of research contribute to the further development and implementation of 3D measurement methods in the shipbuilding industry, which provide more accurate, efficient, and innovative solutions for various engineering tasks.

Conclusions

The detailed analysis of mesh models in 3dReshaper involves comparing point clouds from Laser Control, Agisoft PhotoScan, and Phi.3D software to reference geometric measurements obtained from laser tracker Leica AT960LR.. Time and cost estimates for the four methods of three-dimensional measurements are also presented in this paper.

Laser scanning with Z+F Imager 5016 is more accurate than industrial photogrammetry and handheld scanning. The maximum differences between mesh models based on the laser scanning and laser tracker measurements are +7mm and -9 mm. 87% of the vectors have a length less than 1.5 mm. The fastest method (approximately 20 minutes) for scanning the template is handheld with the DPI-7 and Phi.3D from DotProduct company. The handheld scanning with the DPI-7 and photo-based scanning with the Nikon D2Xs camera and Agisoft PhotoScan software can be used for small projects, considering the economy of the working time and smaller prices.

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ПОРІВНЯННЯ СУЧАСНИХ МЕТОДІВ 3D-ВИМІРЮВАННЯ ДЛЯ ВИРІШЕННЯ ЗАДАЧ СУДНОБУДІВНОЇ ПРОМИСЛОВОСТІ

У роботі розглянуто сучасні технології 3D-вимірювань при виробництві суднобудівних деталей. Для дослідження виготовлено спеціальний шаблон ділянки кіля. Вимірювання шаблону виконані за допомогою лазерного трекера, лазерного сканування, промислової фотограмметрії та ручного сканування. У дослідженні для 3D-вимірювань використано наступне обладнання: лазерний трекер Leica Absolute Tracker AT960-LR, лазерний сканер Z+F Imager 5010, фотокамера Nikon D2Xs для промислової фотограмметрії, ручний сканер DPI-7 від DotProduct. Усі зібрані дані було імпортовано в програмне забезпечення 3DReshaper для порівняння. Проведено порівняння точності для конкретного використаного у дослідженні обладнання. Також у дослідженні надані рекомендації щодо оптимального використання обладнання та програмного забезпечення. Автори представляють оцінку витрат і часу, витраченого на вимірювання. Результати дослідження дозволять ефективно приймати рішення щодо вибору оптичного обладнання та методів 3D вимірювання в суднобудівній промисловості.

Ключові слова: 3D вимірювання, лазерний трекер, лазерне сканування, промислова фотограмметрія, ручне сканування.

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