Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(2), 1–15
https://doi.org/10.12913/22998624/194997
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.08.30
Accepted: 2024.12.15
Published: 2025.01.01

Test and comparison of different digitalization techniques for objects with surfaces difficult to scan

Michał P. Kowalik[1*], Filip Pelowski[2], Ignacy Lipowiecki[1]

[1] Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, ul. Nowowiejska 24, 00-665 Warszawa, Poland
[2] Faculty of Electrical Engineering, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland
* Corresponding author's e-mail: michal.kowalik@pw.edu.pl

ABSTRACT

This article compares three widely used digitalization technologies: photogrammetry, structured light 3D scanning, and computer tomography. The comparison was conducted in terms of the quality and accuracy of reproducing the geometry of scanned objects, the complexity of the measurement process, its duration, and costs. One of the research assumptions was that during scanning, no interference with the surface of the scanned object was allowed (e.g., using matting sprays or applied markers), which simulated conditions such as scanning museum exhibits. The selected objects for the research had various challenging characteristics for scanning, such as highly glossy, matte, porous, or blurry surfaces, and were made of different materials such as metal, wood, or plastics. The article briefly discusses the operation of each tested technology, the methods and steps taken to obtain the final 3D models, and presents their comparison. The research showed that highly glossy surfaces posed the greatest challenge for photogrammetry and structured light scanning, while high density and thickness of the object negatively affected the quality of results obtained using computer tomography. The highest accuracy in geometric reproduction was achieved using the most advanced and costly computer tomography, whereas the lowest accuracy was observed with the least expensive technique, photogrammetry. Both methods require lot of time, knowledge and skills from the operator to achieve best results. Often, the structured light scanner proved to be the best solution, combining simple and fast operation with very satisfactory results in terms of accuracy and detail in reproducing the real object.

Keywords: 3D scanning, photogrammetry, structured light scanners, CT scan, digitalization.

INTRODUCTION

It can be assumed that advances in computational power and programs have the potential to facilitate changes in the way the built environment is designed, constructed and managed today. Computational intelligence is being used in a variety of contexts, from urban design to architectural design and even industrial design. A number of computational methods have been developed for both generating new [1–3] and evaluating existing [4, 5] urban developments. It would be remiss of us not to mention the relatively new studies on crowd simulations, which have been used to great effect for safety & comfort [6, 7] in both architectural and urban environments, as well as for the layout optimization [8]. It has been suggested that modern means of modular systems and automation could be beneficial in a number of areas related to urban and architectural environments. There is a view that they could contribute to improvements in the safety of pedestrians [9] and creating barrier-free environment [10]. Moreover, some unusual computational concepts that emerged from pure mathematics and informatics, e.g.: CA (cellular automata), have been implemented in many aspects of the built environment such as buildings, infrastructure or transportation. CAs have been used for architectural design [11, 12], e.g.: as a form-generator in highly populated residential buildings [13], and for both shading purposes and aesthetics on building façades [14, 15]. Nevertheless, in order to use computational tools, it is often necessary to digitize the information from the physical world. There is an increasing number of ways to utilize new and continuously improved techniques for digitizing real objects. Various 3D scanners, such as laser or structured light scanners, are at the forefront in this field. Depending on the device, they allow reproducing object geometries with accuracy up to 0.1mm [16] or higher [17], and in the case of structured light scanners, also gathering information about the color of the scanned object. They find applications in areas such as quality control [18] or reverse engineering [19]. An important advantage of optical methods is that they are non-destructive methods, even when used for strength testing [20].

Another popular digitization technique is photogrammetry. It allows reproducing object geometry with satisfactory accuracy (sometimes comparable to the accuracy achieved by structured light 3D scanners), but its greatest advantage is the excellent reproduction of object colors. Initiating photogrammetric endeavors necessitates no more than a proficient camera, a modicum of photographic skills, and appropriate software, abundantly available on the market, including some freely accessible options. Consequently, photogrammetry finds wide application in diverse fields, such as the development of computer games [21], the reconstruction and visualization of architectural structures and museum artifacts [22], medical contexts, and even experimatal testing and [23] forensic analysis of traffic accidents [24, 25]. An advanced scanning technique is also computer tomography. It not only enables the acquisition of highly accurate data (with a manufacturer-declared minimum pixel size of 3 µm [26]) regarding the geometry of the scanned object but, unlike the previously mentioned technologies, tomography also allows for exploration of the object's interior. The most widespread domain where computer tomography is applied is medicine. On combining the fields of mechanics and medicine, it can reduce the complicated and time-consuming modeling of body parts [27]. However, it finds its utility in quality control as well as in the examination of remains and cultural heritage objects [28]. The mentioned techniques can also be utilized to transfer real-world objects into the virtual reality environment, such as the metaverse. Another application could be the digitization of museum collections [29, 30]. Due to the high cultural and historical value of such collections, it is impossible to touch them during visits, which significantly hinders the perception of culture by visually impaired or blind people, for whom the only current solution is a verbal description of the objects in front of them. Digitized collections can be properly processed and then reproduced using 3D printing techniques. Printed replicas of originals can greatly facilitate cultural appreciation for people with visual impairments. Comparison of different 3D scanning techniques has been performed multiple times [31–33]. The results are consistent, indicating that, in comparison between photogrammetry, structured light scanning, and tomography, structured light scanning is considered the most favorable technique due to its accuracy in reproducing object surfaces, basic textures, time efficiency, and costs. However, satisfactory results were achievable with all tested technologies. It is important to note that the comparisons were based on scans of a small number of objects (from 1 to 4), and furthermore, the scanned objects had very few features that could hinder the scanning process.

MATERIALS AND METHODS

During the research, three 3D scanning technologies were compared. These were: photogrammetry, handheld structured light 3D scanning, and computer tomography. The choice of these methods was dictated by their popularity and the availability of equipment. The devices used to obtain scans for each of these technologies were as follows: a Canon EOS 5D Mark IV camera with a resolution of 30.4 megapixels for photogrammetry, a handheld structured light 3D scanner Artec Eva with a manufacturer-declared accuracy of up to 0.1 mm and a resolution of up to 0.5 mm, and a computer tomography scanner Nikon XT H 225 characterized by a maximum beam energy of 225 kV, power of 450 W, a minimum pixel size of 3 µm, and a working area of 432×432 mm.

Selection of objects for research

During the selection of research objects for scanning, attention was paid to ensuring that they posed challenges for the aforementioned technologies by possessing various features that hinder scanning. These challenges included the presence of glossy surfaces, which pose difficulties for photogrammetry and structured light scanners due to significant light scattering, or porous surfaces, which may introduce unwanted noise. Another challenge was the presence of easily deformable objects, as scanning them may require changing their position, potentially leading to inconsistent relative alignments of their elements, resulting in layered results. Additionally, fuzzy surfaces such as hair or fiber materials were included, as they reflect light chaotically, causing noise. Thin-walled objects also present a challenge, as aligning and merging scans of their main surfaces can be problematic due to the limited information about the area between them. The selected objects were also made of various materials such as metal, wood, or plastics. The difference in material density or the presence of highly dense or very low-density fragments within the object may pose challenges for computer tomography. Taking into account all these features and types of objects, a comprehensive set of research objects was assembled, as presented in Table 1. Certainly, the selection of materials could be extended to include others that might pose challenges during digitization attempts using various methods, such as porcelain or stone. However, these materials would replicate the characteristics already identified as problematic for the digitization process. Therefore, it was decided not to expand the list of examined objects.

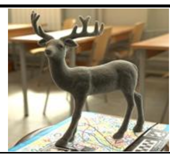
Measurement and data capturing

Photogrammetry

In order to obtain 3D models of selected objects using the photogrammetry method, the first step involved preparing a properly illuminated setup that allowed the operator to walk around the object freely and capture it from every angle. Sometimes, to create a complete model, it was necessary to capture two series of photos with changes in the object's orientation between them (e.g., in the case of cubes). Care had to be taken to ensure that the relative positions of elements within the frame did not change during the series of photos, as this could lead to inaccurate or erroneous matching, resulting in blurry or entirely flawed models. A crucial aspect of taking photos was ensuring that all images of the photographed object were sharp and steady. The more complex the object, the more photos needed to be taken.

For the selected research objects, the number of photos taken per object ranged from 218 for the "lady with bike" figurine to 550 for cube1. To reconstruct the flowers, 331 photos and 779 frames extracted from a short film were utilized.

Table 1. Selected objects and their features

Name		Cube1	Cube2	Axe	Reindeer	Flowers	Lady with bike
Real life photo							
Feature							
Type of surface	Detailed	X	X	X	X	X	X
	Glossy	X	X				X
	Matte			X	X	X	
	Porous			X		X	X
	Fuzzy				X	X	
Material	Wood			X			
	Metal			X			X
	Plastic	X	X		X	X	
Other	Thin-walled					X	X
	Easily deformable	X	X			X	
	Hard to reach fragments	X	X	X	X	X	X

The decision to combine classical photogrammetry relying solely on photos with extracting individual frames from the film was dictated by the ability to better approach the object's nooks and crannies and capture many irregular surfaces of the object. The photographed objects were placed on a colored background, and small elements were arranged next to them to facilitate the software's matching of photos. Additionally, a specially designed and printed scale bar was used to introduce the actual scale, ensuring that the resulting models possessed appropriate dimensions. An example of the object arrangement during measurements and the use of a scale bar is shown in Figure 1.

The acquired images can undergo basic graphic processing to adjust exposure, brightness, or contrast, aiming to achieve a more precise model or improved textures. Subsequently, the next step involves importing the images into appropriate software (in the case of the present study, Bentley's ContextCapture was utilized), followed by initiating procedures for image matching and 3D model creation in the form of a triangle mesh. Results obtained through photogrammetry may vary depending on factors such as the number of captured images, camera quality, time devoted to image processing, and the specific software employed.

Structural-light 3D scanner

The first step in scanning objects with a structured light scanner is to prepare the appropriate scene and location. In contrast to photogrammetry, dimly lit or even dark environments are preferable in this case, as they provide greater contrast between the pattern projected by the 3D scanner and the object surface, thereby facilitating the collection of necessary data by the 3D scanner's detector. During scanning, the object can be repositioned to capture various fragments, but it is essential to ensure an adequate number of common points between scans for manual alignment. Additionally, other environmental elements can be utilized to facilitate the alignment of multiple scans. After acquiring and aligning the scans, unnecessary elements are removed, and global registration and fusion are performed to generate a final model. During the scanning of a cube, the glossy surface posed numerous challenges. The scanner could only collect data when positioned perpendicular to the cube's faces. Any other orientation rendered the cube invisible to the scanner, leading to tracking loss and the inability to capture more than one side of the cube. This issue was addressed by placing several background elements behind the scanned cube to diversify the background and introduce more tracking points (Figure 2). These points served as anchors for algorithms to match recorded data when the cube became invisible to the 3D scanner's detector. To capture the entire cube, the background elements had to be rearranged multiple times, and then all measurements were merged together.

Computer tomography

Working with a computer tomograph requires minimal operator attention but demands significant knowledge regarding parameter selection for scanning and subsequent result processing. After placing the object in the chamber (Figure 3), setting scan parameters such as beam energy, power, and the number of measurements is necessary.

a) b) c)

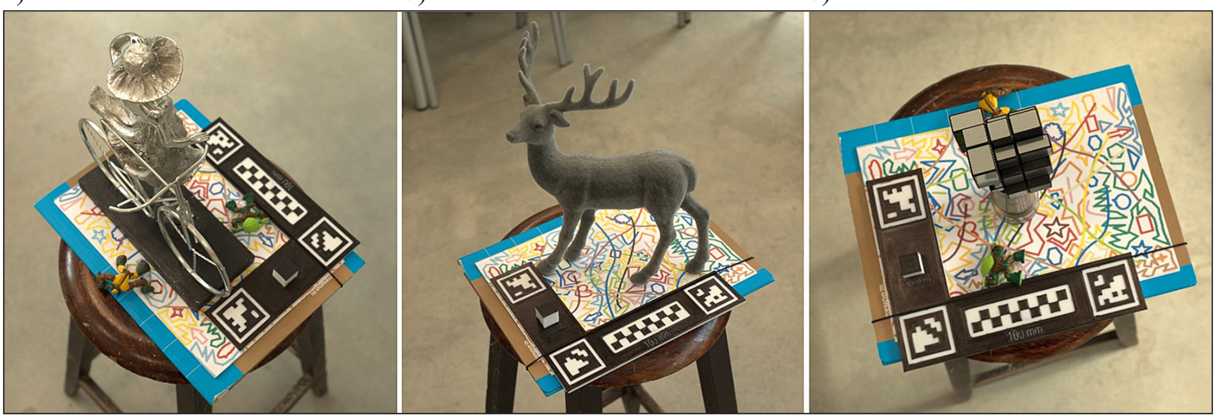


Figure 1. Exemplary arrangement of objects for photogrammetry: lady with bike (a), reindeer (b) and cube2 (c)

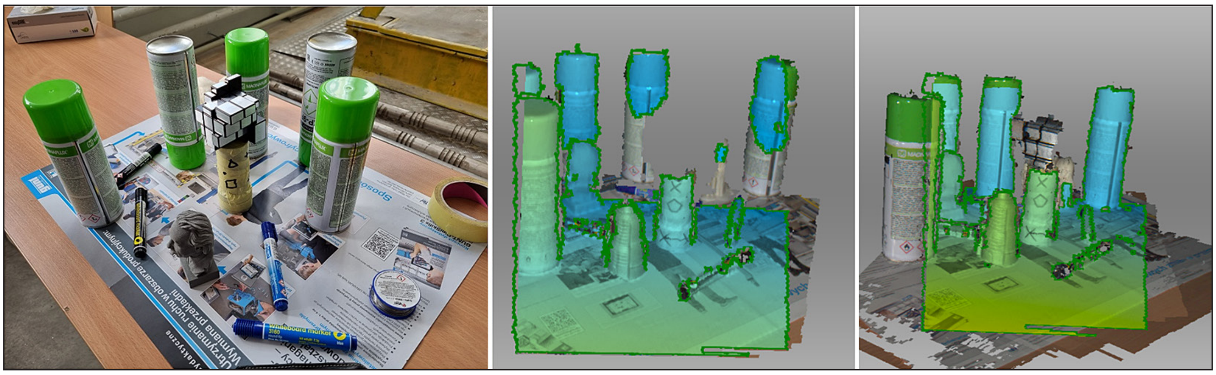


Figure 2. Scenery for scanning cube2 and the view from the scanner

a) b) c)

Figure 3. Sample items in the tomograph chamber: cube2 (a), axe (b) and flowers (c)

The choice of these parameters can yield results of varying quality. Once the settings are approved, the tomograph performs the specified number of measurements, and then, from the collected data, the desired parts need to be separated using appropriate software. Depending on the scanned part, these could be external or internal elements.

RESULTS

Due to the project's primary focus on geometric fidelity rather than textural accuracy, only the discussion concerning the acquired geometric models will be conducted. The most significant challenge in photogrammetry arises with objects having glossy and reflective surfaces. Due to light reflections during image capture on these surfaces, the final result is far from satisfactory. This is evident in the model of the lady with a bike, where mirrored elements have a very porous surface instead of a smooth one, and details are either heavily blurred or entirely invisible. The issue with glossy surfaces is also apparent in both cubes, where minor shadows during image capture caused flat surfaces to become wavy or distorted. Thin-walled elements and surfaces that are difficult to access due to the object's complex geometry also present problems. The flowers are a prime example, where the resulting model had many holes, and after digital patching, the obtained geometry may differ from reality. Some of the described problems are illustrated in the Figure 4. Similarly to photogrammetry, mirrored surfaces pose significant challenges for structured light scanners. It becomes exceedingly difficult to scan objects with mirrored surfaces unless they are planar (e.g., as in the case of 'cube2'). However, even in such cases, extensive effort is required to successfully scan the object, and the resulting scans often contain considerable noise that necessitates manual removal, as depicted in Figure 5. Despite numerous attempts, we were unable to obtain any model of the 'lady with bike' (Figure 6) because this object was completely unregistered by the 3D scanner. Additionally, during scanning, it was evident that there were issues with thin elements such as bicycle

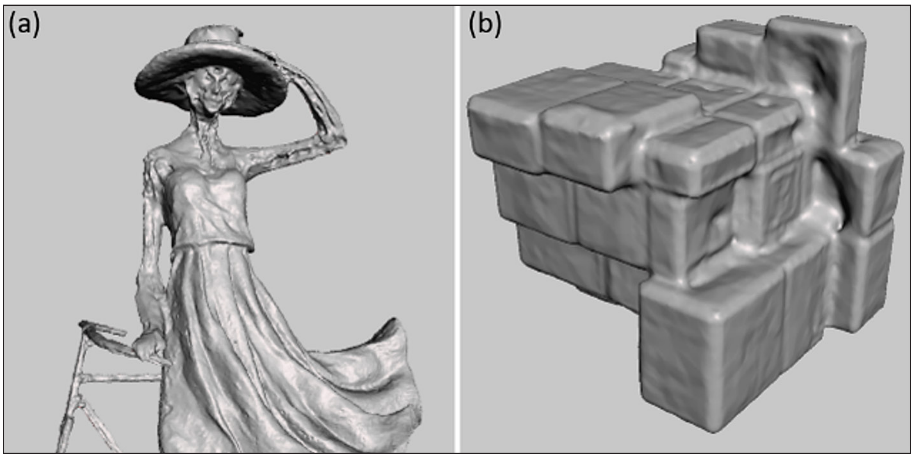


Figure 4. Example of problems with photogrammetry: lady with bike (a) and cube2 (b)

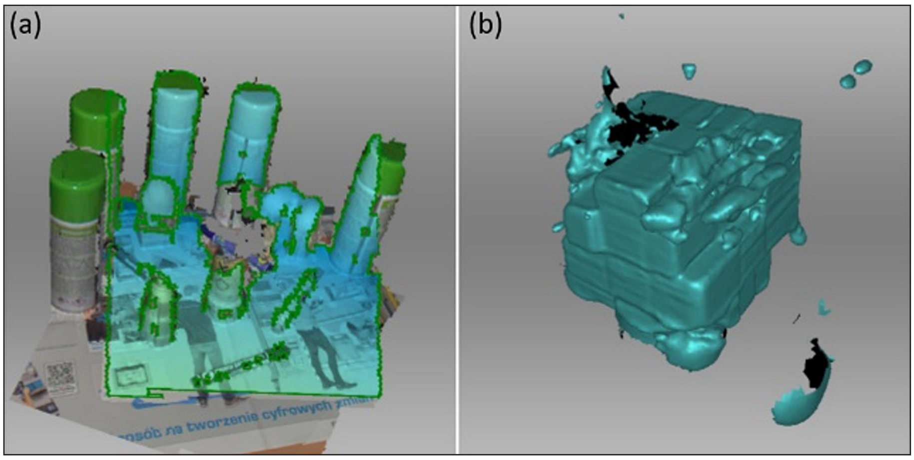


Figure 5. ‚Disappearing' cube2 (a) and noises around it (b)

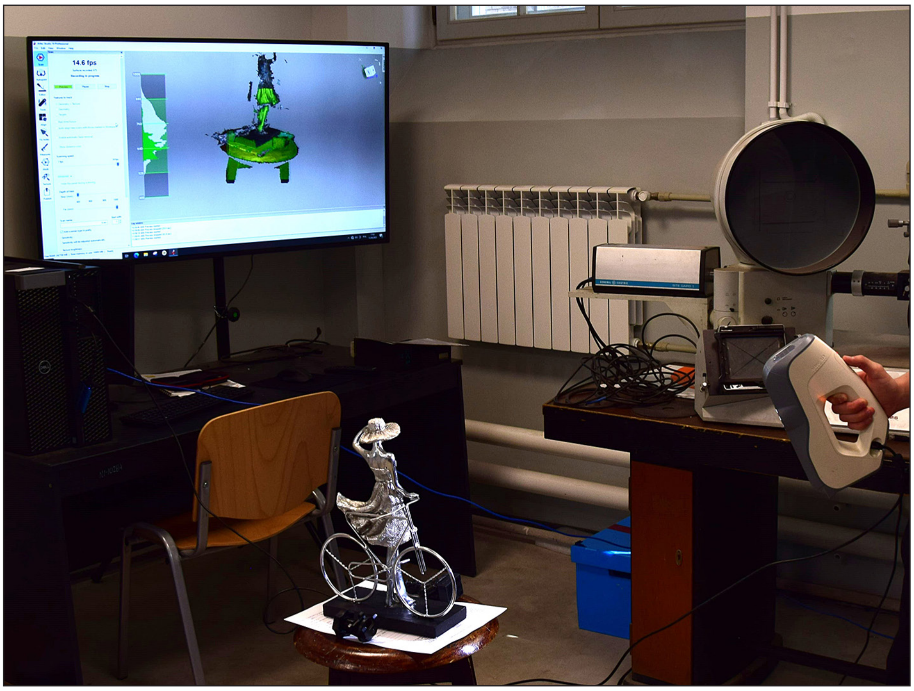


Figure 6. Trying to scan lady with bike

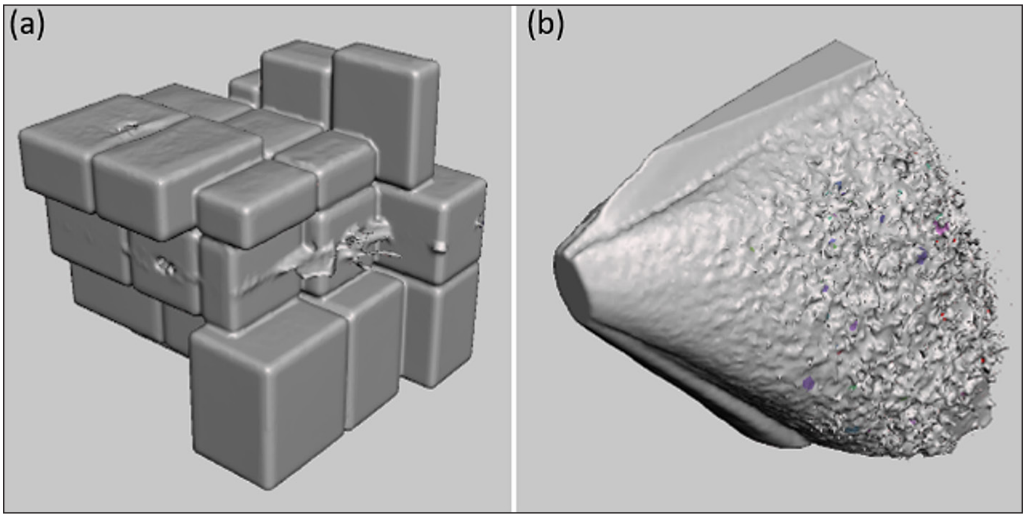


Figure 7. Problems with scanning cube2 (a) and axe (b) using a CT scanner

spokes, as these would also disappear from view. For the computer tomograph, shiny surfaces posed no problem. However, poor results were obtained when scanning an axe, as its dense, metal head proved too thick to scan, resulting in a significant amount of noise and disturbances that hindered model extraction. Attention should also be drawn to objects with flat surfaces, as positioning them parallel to the radiation beam in the tomograph chamber may result in significant noise, as depicted in Figure 7.

Comparison of results

Table 2 presents a graphical comparison of results obtained by different scanning methods along with images of the actual scanned objects. The analysis of this table allows for selecting elements that most closely resemble the original object, which may not always be adequately reflected in parameters such as accuracy. Analysis of the resulting triangle meshes allows for an evaluation of surface continuity and the level of detail representation. Table 3 provides a comparison of two important scanning parameters.

The first parameter is the size of the triangle meshes obtained as the final result of each method. The second parameter is the total time required to complete the measurement process and generate the 3D model. Another important parameter is the accuracy of reproducing physical sizes. Measurements taken by computer tomography were considered as reference due to its highest accuracy among the selected scanning methods [34]. To verify discrepancies between the obtained 3D models, they were overlaid, and a discrepancy map between the examined models was generated, where the reference model was always the one obtained using computer tomography (see Figure 8–10). Discrepancies were examined within a range of up to 3 mm, and the tolerance at which the model is presented in green on the graphical drawing was set at 0.2 mm. Each of the drawings also presents a series of measurements showing discrepancies at a given point (see Figures from 11 to 14). Some parameters considered during the comparison of models are presented in Table 4. The results obtained indicate a slight advantage of 3D scanning over photogrammetry in terms of geometric accuracy, however, for the examined objects, these differences are minimal and may be imperceptible in many applications.

Gray color indicates scans from computed tomography. Blue color represents results obtained from photogrammetry, and green color denotes scans from structured light 3D scanner. a) cube1 photogrammetry results overlaid on computed tomography results, b) cube2 photogrammetry results overlaid on computed tomography results, c) cube1 structured light 3D scanner results overlaid on computed tomography results, d) cube2 structured light 3D scanner results overlaid on computed tomography results.

An interesting phenomenon can be observed when comparing the model of a reindeer obtained using computer tomography, both with the model obtained using photogrammetry and with the model obtained using a 3D scanner. Large discrepancies in one direction (models from computer

Table 2. Comparison of results

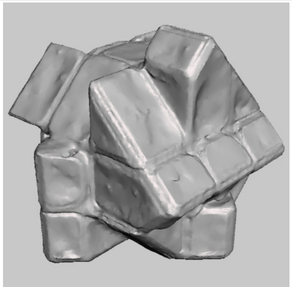
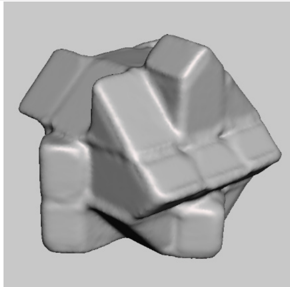
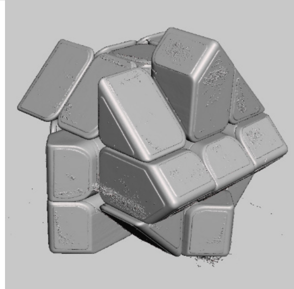
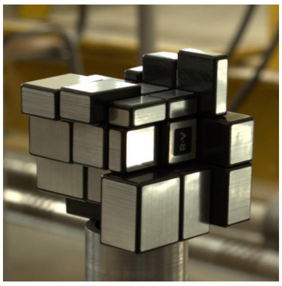
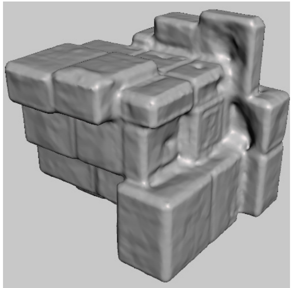
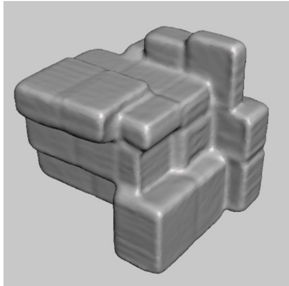
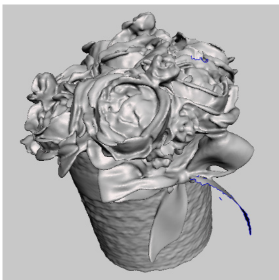
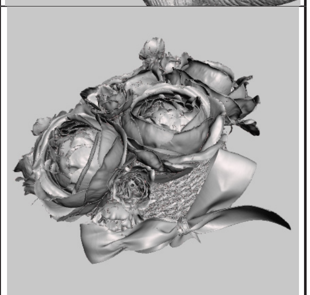
Real object	Photogrammetry	Structural light scanner	Ct scan
			
			
			
			
			
			

Table 3. Parameters of scanned models

Parameter		Photogrammetry	Structured light	CT scan
Reindeer	Number of triangles [k]	58.1	345.8	2950
	Working time [h:min]	01:15	00:25	01:40
Cube2	Number of triangles [k]	29	54.5	5685.3
	Working time [h:min]	01:35	00:35	01:50
Lady with bike	Number of triangles [k]	63.2	-	428.3
	Working time [h:min]	01:15	-	01:35

Table 4. Results of 3D model comparisons

Parameter		Photogrammetry	Structured light
Cube	Absolute distance [mm]	1.0954	1.0691
	Absolute deviation [mm]	0.9628	0.9456
	Signed distance [mm]	-0.495	-0.4724
	Root mean square [mm]	1.269	1.261
Cube2	Absolute distance [mm]	0.83	0.77
	Absolute deviation [mm]	0.841	0.776
	Signed distance [mm]	-0.2987	-0.313
	Root mean square [mm]	1.067	1.012
Reindeer	Absolute distance [mm]	1.1838	1.3832
	Absolute deviation [mm]	0.8442	0.73
	Signed distance [mm]	0.62	0.898
	Root mean square [mm]	1.222	1.205

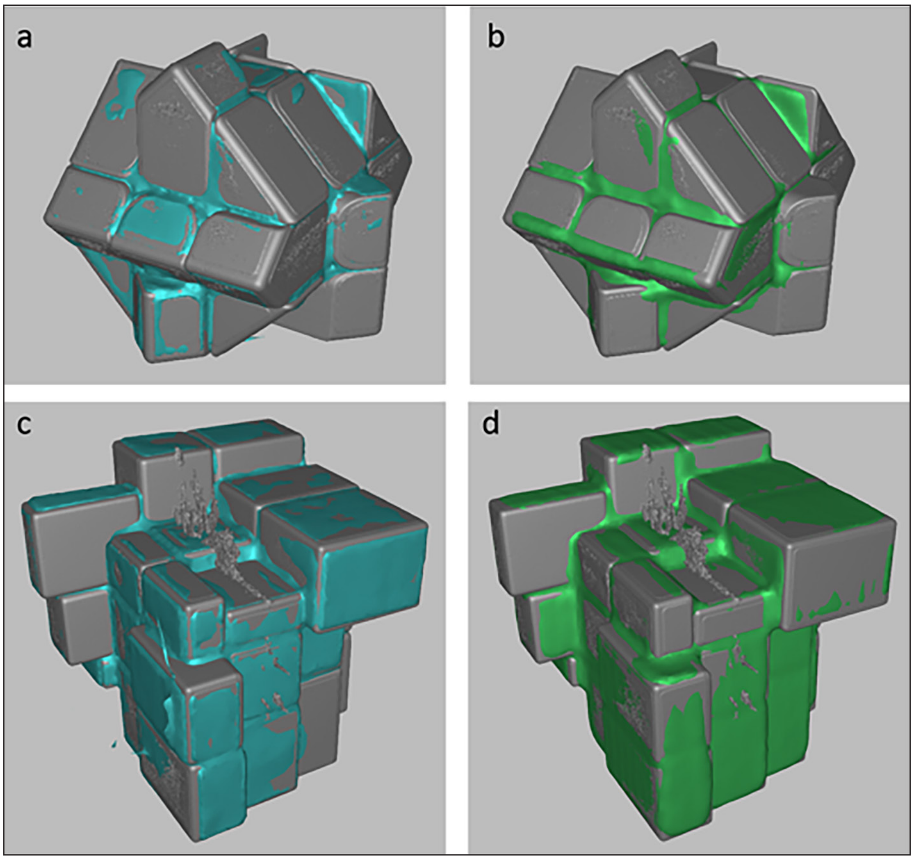


Figure 8. View of overlaid triangular meshes

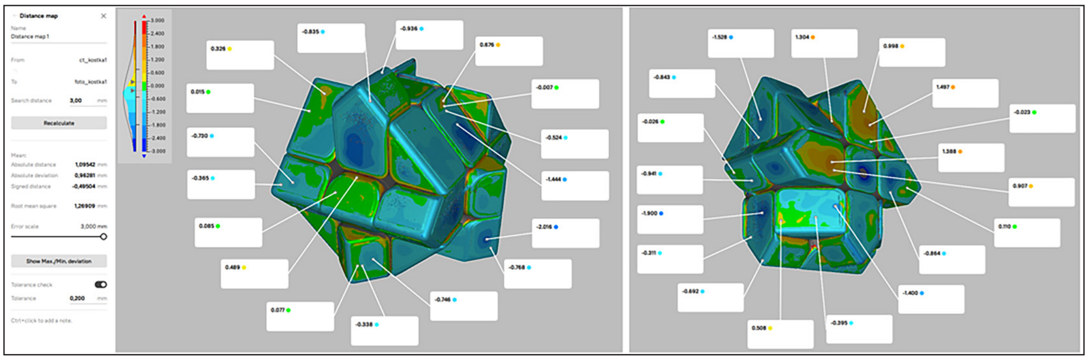


Figure 9. 3D distance map between computed tomography scan and photogrammetry for cube1

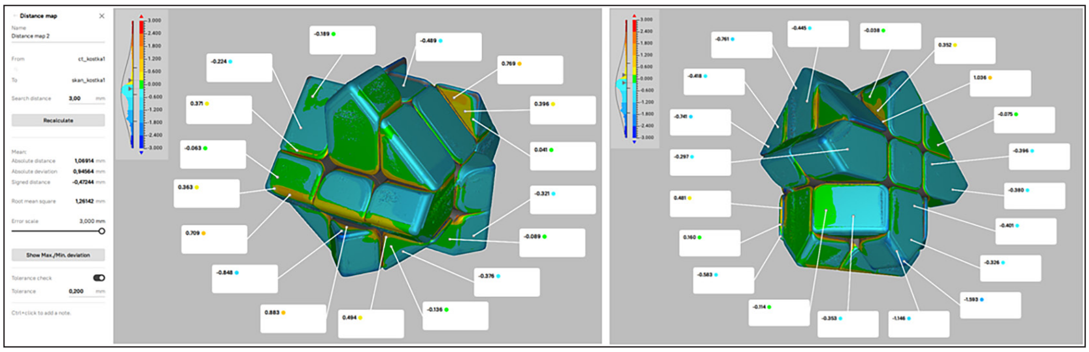


Figure 10. 3D distance map between computed tomography scan and structured light 3D scanner for cube1

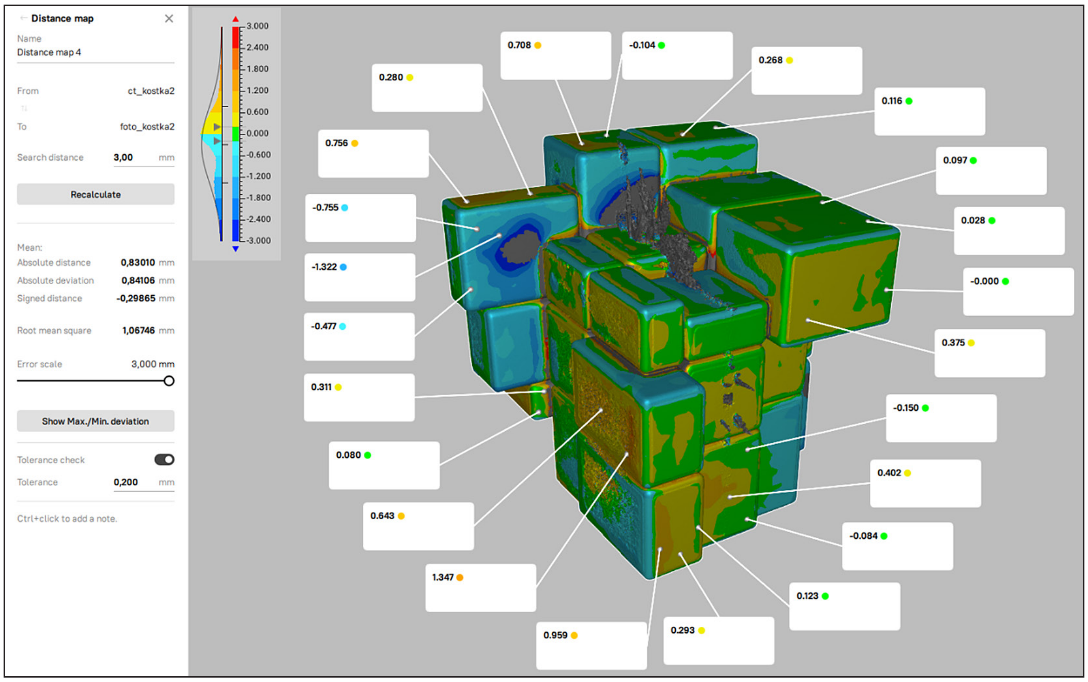


Figure 11. 3D distance map between computed tomography scan and photogrammetry for cube2

tomography appear to be smaller than the others) prompted further analysis. Comparing the models from photogrammetry and the 3D scanner reveals smaller discrepancies (see Figure 15).

Overlaying the models and then examining them (see Figure 16) allowed for the following conclusions. Optical methods, such as 3D scanning and photogrammetry, completely

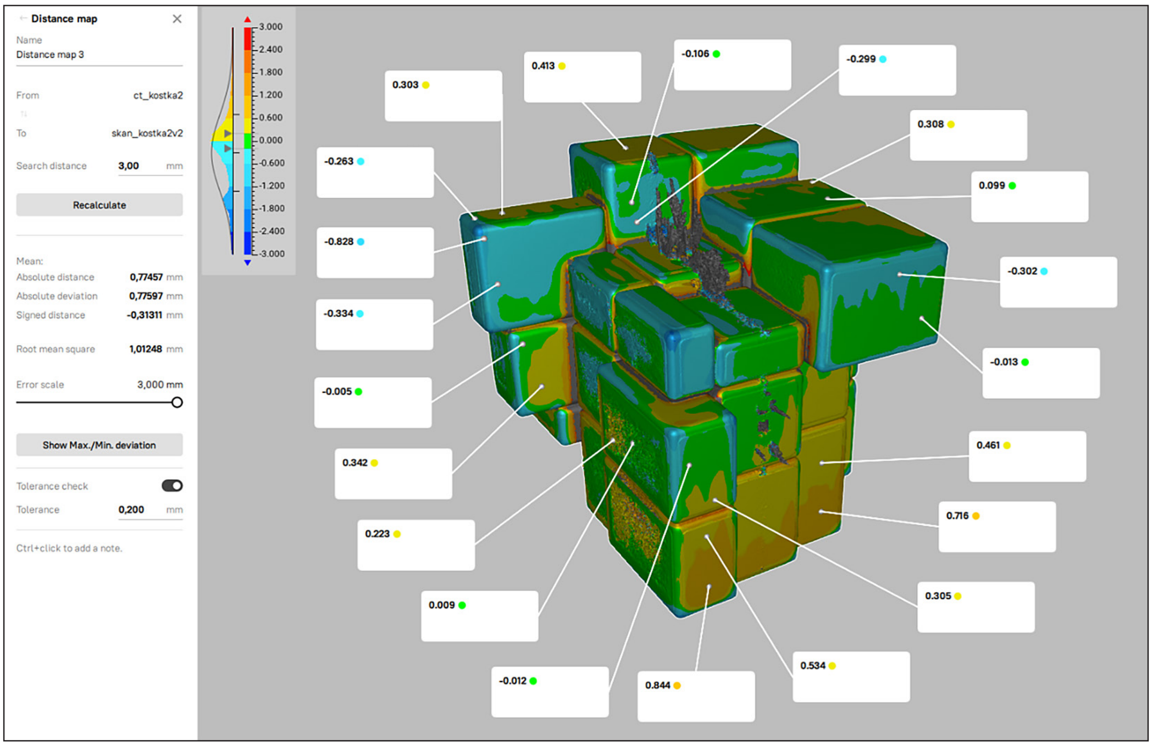


Figure 12. 3D distance map between computed tomography scan and structured light 3D scanner for cube2

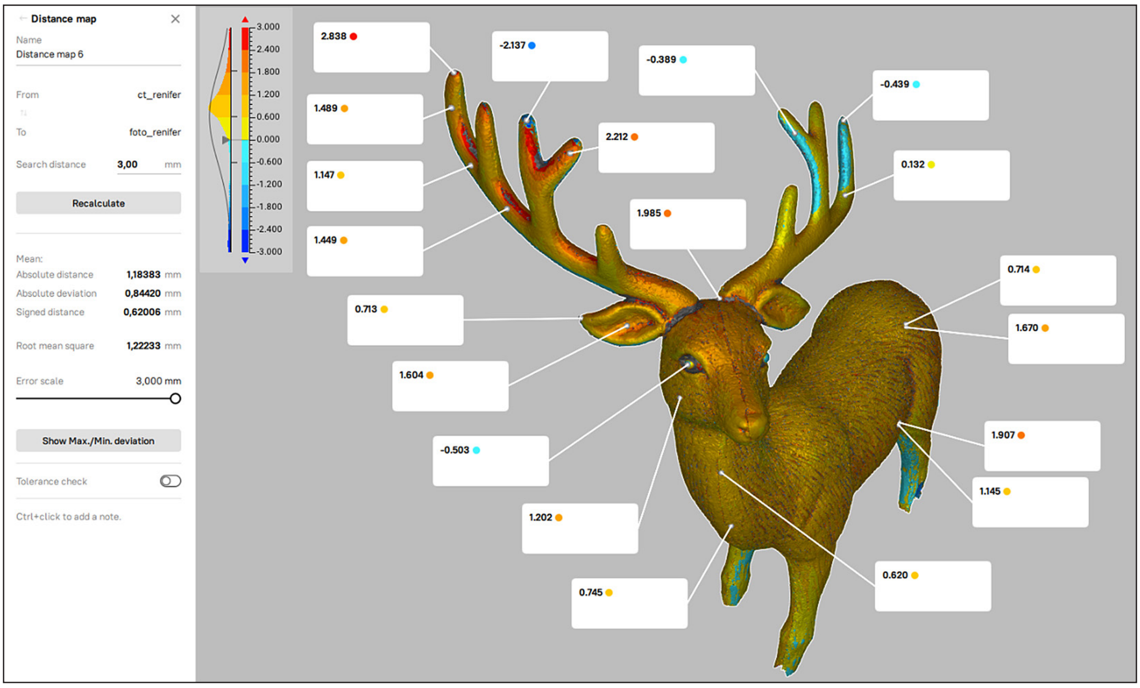


Figure 13. 3D distance map between computed tomography scan and photogrammetry for reindeer

captured the external surface of the model, approximating its fur to a continuous surface. In the case of computer tomography, due to large differences in material density, only the internal structure of the material was captured, resulting in an effect as if the first layer of the model, approximately 1 mm thick, had been removed. The results obtained using computer tomography exhibit a very high level of detail. For the selected objects examined, the least detailed models were obtained using photogrammetry. According to Table 3, both of these methods are

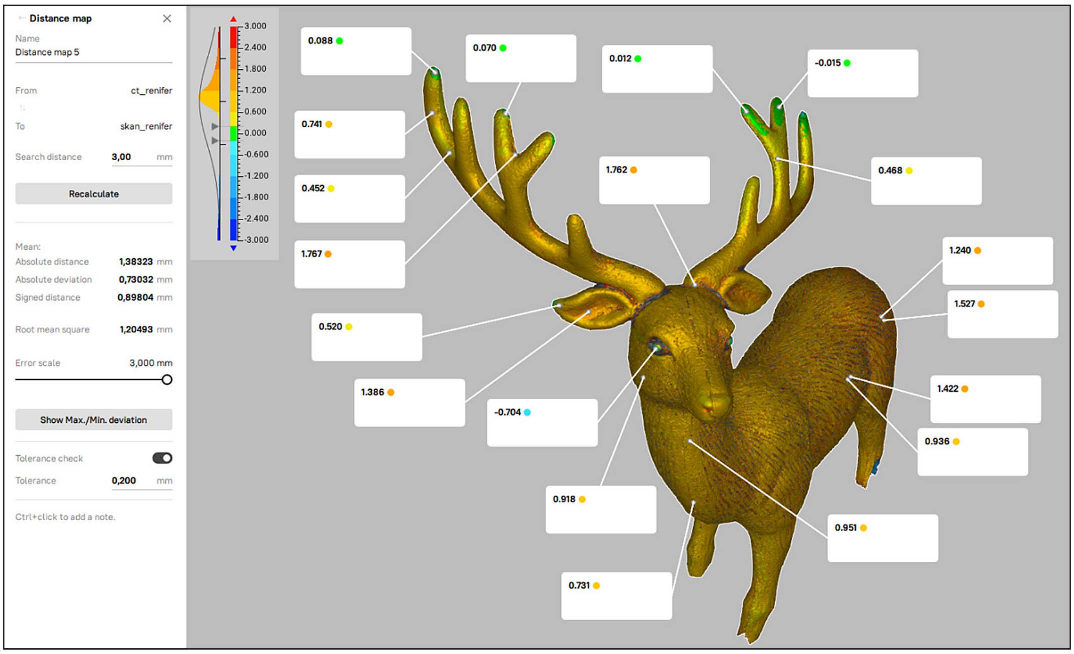


Figure 14. 3D distance map between computed tomography scan and structured light 3D scanner for reindeer

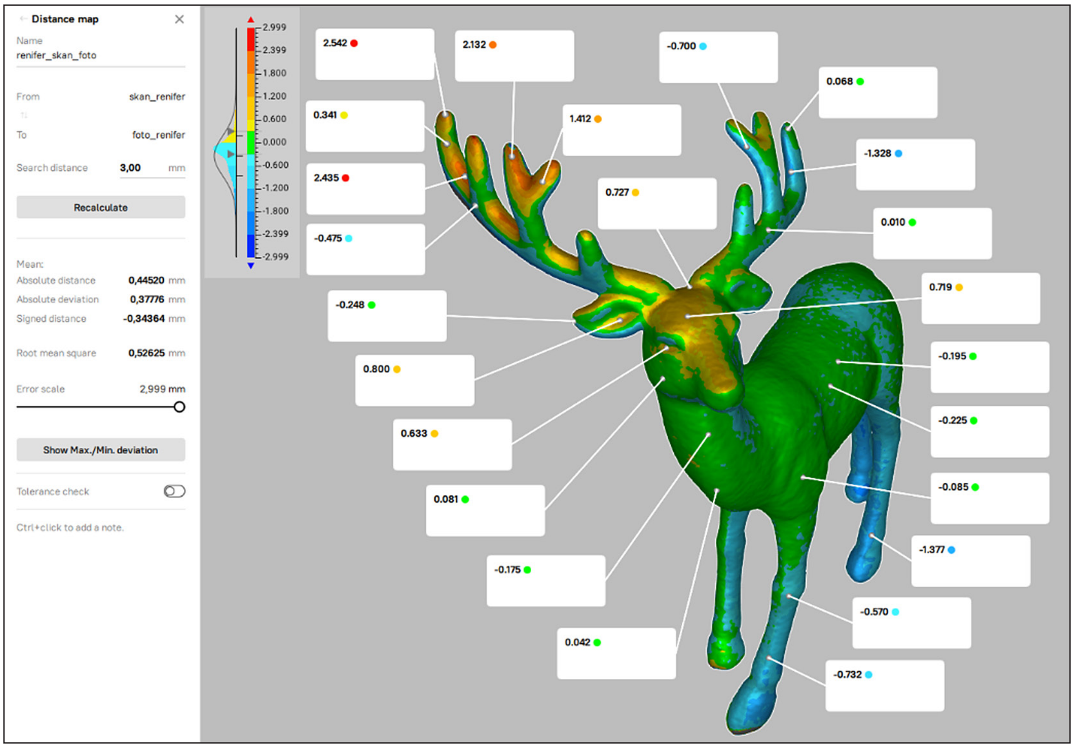


Figure 15. 3D distance map between computed structured light 3D scanner and photogrammetry for reindeer

characterized by significantly longer working times compared to structured light scanning. This is due to the need to process a large amount of data obtained during scanning or from captured photographs, as well as the complexity of the triangulation and image matching process in photogrammetry, or the time required to scan the object itself using tomography. Nearly half of the time required to obtain a model of the real object using computer tomography may be attributed to the time spent exporting the model, during which a mesh of many thousands of triangles is created to ensure such precise geometry representation.

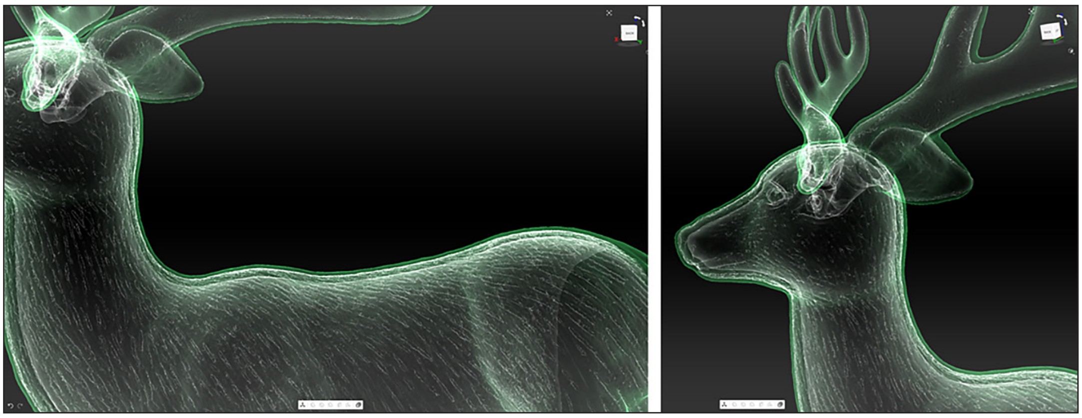


Figure 16. View of overlaid computed tomography scan and results from structured light 3D scanner in X-ray view

CONCLUSIONS

All the tested 3D scanning techniques have their advantages and disadvantages. When digitizing small objects commonly found in museums, computer tomography typically requires the most time. Achieving optimal results with this method demands the highest level of knowledge and experience from the operator. Larger objects may sometimes not fit into the Tomograph chamber, which constitutes a serious limitation of this method. Additionally, the device itself is not very portable and incurs significant costs (on the order of hundreds of thousands of dollars). However, the advantage of computer tomography lies in its ability to produce nearly flawless models of the vast majority of scanned objects.

Photogrammetry also has many advantages. It is the cheapest technique among those compared, allowing for the scanning of objects of any size and enabling the capture of highly detailed textures. The cost of obtaining models using this technique depends on the equipment and software used, but basic results can be achieved using a smartphone camera and free software. Like computer tomography, photogrammetry also requires knowledge and skills from the operator, as the final result largely depends on the quality of the captured images, making it highly sensitive to lighting conditions. Results obtained using photogrammetry were usually the least accurate in terms of reproducing the geometry of the scanned object. To improve the final result, it is possible to use specialized photogrammetric chambers, better lighting, highly specialized cameras, or, in the case of shiny elements, cross-polarization techniques. Due to the large amount of data to process, image processing and obtaining a 3D model can take a long time, and sometimes, with certain types of surfaces, the final result may still be unusable.

The simplest and fastest scanning method among those tested turned out to be the use of structured light scanning. This method also allows for scanning objects of any size (although it may be necessary to use different scanners) and obtaining basic textures. The results obtained in most cases were characterized by very good reproduction of the geometry of real objects, with serious problems only appearing on highly reflective surfaces. However, if intervention in the scanned object is possible, such as using a matte spray, this obstacle can be overcome. Combining all the aforementioned advantages of scanning using structured light scanners with the drawbacks, the impact of which can sometimes be significantly reduced, and the price of a good quality device (from $10,000 to $50,000), makes this method optimal for digitizing real objects.

The results obtained largely coincide with those presented in earlier studies comparing the mentioned 3D scanning methods. Structured light scanning can again be considered the optimal method; however, special attention should be paid to the presence of features that make scanning difficult (such as reflective surfaces), as in some cases, the use of another discussed technique may be more favorable.

It is worth mentioning the possibility of combining several scanning methods and leveraging the greatest advantages of each [35]. A model obtained in this way could, for example, have precise geometry obtained using structured light scanning or computer tomography, along with texture overlaid on it collected using photogrammetry.

Acknowledgements

The project "Improving access to culture and activation of the disabled and socially excluded" GOSPOSTRATEG-VI/0022/2021 is co-financed by The National Centre for Research and Development

REFERENCES

1. Pérez-Martínez, I., Martínez-Rojas, M. and Soto-Hidalgo, J.M., 2023. A methodology for urban planning generation: A novel approach based on generative design. Engineering Applications of Artificial Intelligence, 124, 106609.
2. Zhang, X., Wang, X., Du, S., Tian, S., Jia, A., Ye, Y., Gao, N., Kuang, X. and Shi, X. A systematic review of urban form generation and optimization for performance-driven urban design. Building and Environment, 2024, 111269.
3. Jiang, F., Ma, J., Webster, C.J., Chiaradia, A.J., Zhou, Y., Zhao, Z. and Zhang, X. Generative urban design: A systematic review on problem formulation, design generation, and decision-making. Progress in planning, 2024, 180, 100795.
4. Zawidzki, M. Automated geometrical evaluation of a plaza (town square). Advances in Engineering Software, 2016, 96, 58–69.
5. Zare, Z., Yeganeh, M. and Dehghan, N., Environmental and social sustainability automated evaluation of plazas based on 3D visibility measurements. Energy Reports, 2022, 8, 6280–6300.
6. Li, J., Chen, M., Wu, W., Liu, B. and Zheng, X. Height map-based social force model for stairway evacuation. Safety Science, 2021, 133, 105027.
7. Martinez-Gil, F., Lozano, M. and Fernández, F., Emergent behaviors and scalability for multi-agent reinforcement learning-based pedestrian models. Simulation Modelling Practice and Theory, 2017, 74, 117–133.
8. Zawidzki, M., Chraibi, M. and Nishinari, K. Crowd-Z: The user-friendly framework for crowd simulation on an architectural floor plan. Pattern Recognition Letters, 2014, 44, 88–97.
9. Zawidzki, M. Optimization of multi-branch Truss-Z based on evolution strategy. Advances in Engineering Software, 2016, 100, 113–125.
10. Zawidzki, M. Retrofitting of pedestrian overpass by Truss-Z modular systems using graph-theory approach. Advances in Engineering Software, 2015, 81, 41–49.
11. Herr, C.M. and Ford, R.C. Cellular Automata in architectural design: From generic systems to specific design tools. Automation in Construction, 2016, 72, 39–45.
12. Herr, C.M. and Kvan, T. Adapting Cellular Automata to support the architectural design process. Automation in Construction, 2007, 16(1), 61–69.
13. Araghi, S.K. and Stouffs, R. Exploring Cellular Automata for high density residential building form generation. Automation in Construction 2015, 49, 152–162.
14. Zawidzki, M. Implementing Cellular Automata for dynamically shading a building facade. Complex Systems, 2009, 18(3), 287.
15. Zawidzki, M. and Fujieda, I. The prototyping of a shading device controlled by a Cellular Automaton. Complex Systems, 2010, 19(2), 157.
16. Artec 3D. Home. Available at: https://www.artec3d.com/. (Accessed April 25, 2024).
17. GOM. ATOS Q. Available at: https://www.gom.com/en/products/3d-scanning/atos-q. (Accessed April 25, 2024).
18. Montalti A, Ferretti P, Santi GM. A cost-effective approach for quality control in PLA-based material extrusion 3D printing using 3D scanning. Journal of Industrial Information Integration. 2024, 41, 100660. https://doi.org/10.1016/j.jii.2024.100660
19. Reyno, T., Marsden, C., Wowk, D. Surface damage evaluation of honeycomb sandwich aircraft panels using 3D scanning technology. NDT & E International. 2018, 97. https://doi.org/10.1016/j.ndteint.2018.03.007
20. Rządkowski, W., Tracz, J., Cisowski, A., Gardyjas, K., Groen, H., Palka, M., Kowalik, M. Evaluation of bonding gap control methods for an epoxy adhesive joint of carbon fiber tubes and aluminum alloy inserts. Materials 2021, 14, 1977. https://doi.org/10.3390/ma14081977
21. Statham, N. Use of photogrammetry in video games : a historical overview. Games and Culture, 2020, 15(3), 289–307. https://doi.org/10.1177/1555412018786415
22. Apollonio FI, Fantini F, Garagnani S, Gaiani M. A Photogrammetry-Based Workflow for the Accurate 3D Construction and Visualization of Museums Assets. Remote Sensing. 2021, 13(3), 486. https://doi.org/10.3390/rs13030486
23. Saraczyn R, Deroszewska M, Kowaluk T, Skołek E, Rządkowski W, Myszka D. Supported by 2D and 3D imaging methods investigation of the influence of fiber orientation on the mechanical properties of the composites reinforced with fibers in a polymer matrix. Advances in Science and Technology Research Journal. 2023, 17(3), 170–183. https://doi.org/10.12913/22998624/166101
24. Stehel S, Vertaľ P, Demčáková L. Application of close-range photogrammetry in documenting the location of an accident. Transportation Research Procedia. 2021, 55, 1657–64. https://doi.org/10.1016/j.trpro.2021.07.310
25. Minachi C, Karuppanan G. Advancements in accident

investigation - accident reconstruction and forensics using photomodeler software. International Journal of Applied Engineering Research. 2015, 10, 345–9.

26. Nikon Metrology. Nikon XT H 160/225/450. Available at: http://www.ckpi.net/Catalog_Nikon/Nikon%20XT%20H%20160,225,450.pdf. (Accessed April 25, 2024.)
27. Drelich, E., Tracz, J., Cisowski, A. et al. Force prediction in the cylindrical grip for a model of hand prosthesis. Sci Rep 2023, 13, 17205 https://doi.org/10.1038/s41598-023-43600-1
28. Charlier P, Kissel E, Moulherat C, et al. First in-situ use of a mobile CT-scan for museum artefacts: The quai Branly – Jacques Chirac museum experience. Forensic Imaging. 2020, 20. https://doi.org/10.1016/j.fri.2020.200327
29. Miłosz MM, Montusiewicz J, Kęsik J, et al. Virtual scientific expedition for 3D scanning of museum artifacts in the COVID-19 period – The methodology and case study. Digital Applications in Archaeology and Cultural Heritage. 2022, 26. https://doi.org/10.1016/j.daach.2022.200394
30. Apollonio F.I., Fantini F., Garagnani S., Gaiani M. A photogrammetry-based workflow for the accurate 3D construction and visualization of museums assets. Remote Sensing. 2021, 13(3), 486. https://doi.org/10.3390/rs13030486
31. Böhler W. Comparison of 3D scanning and other 3D measurement techniques. W: Centro Stefano Franscini Monte Verità, Ascona (Ed.). Recording, Modeling and Visualization of Cultural Heritage: Proceedings of the International Workshop. Londyn: Taylor & Francis Ltd; 2006.
32. Freeman Gebler O, Goudswaard M, Hicks B, Jones D, Nassehi A, Snider C, Yon J. A comparison of structured light scanning and photogrammetry for the digitisation of physical prototypes. Proceedings of the Design Society. 2021, 1, 11–20. https://doi.org/10.1017/pds.2021.2
33. Mathys A, Brecko J, Semal P. Comparing 3D digitizing technologies: What are the differences? W: 2013 Digital Heritage International Congress (DigitalHeritage). Marseille, France; 2013, 201–204. https://doi.org/10.1109/DigitalHeritage.2013.6743733
34. Waltenberger L, Rebay-Salisbury K, Mitteroecker P. Three-dimensional surface scanning methods in osteology: A topographical and geometric morphometric comparison. Am J Phys Anthropol. 2021, 174, 846–858. https://doi.org/10.1002/ajpa.24204
35. Lipowiecki I.K., Rządkowski W., Zapał W., Kowalik M.P. Combining the technology of long-range laser 3D scanners and structured light handheld 3D scanners to digitize large-sized objects. Advances in Science and Technology Research Journal. 2023, 17(3), 196–205. https://doi.org/10.12913/22998624/166186