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3D scanning and modeling of highly detailed and geometrically complex historical architectural objects: the example of the Juma Mosque in Khiva (Uzbekistan)

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Abstract

The city centre of Khiva (Uzbekistan), called Itchan Kala, is an architectural complex included in the UNESCO list of tangible cultural heritage. One of the historic buildings in it is the Juma Mosque. It has a simple rectangular structure, but is very large and has 213 deeply carved wooden columns supporting the roof. The article presents the process, problems, and their solutions resulting from the implementation of 3D laser scanning of such highly detailed and geometrically complex historical architectural objects in the conditions of normal tourist traffic. The optimisation of scanning positions, scanning in situ implementation, as well as the processing of the acquired data and the construction of a 3D mesh model of the mosque interior are presented. It is pointed out that scanning such objects with high accuracy and density of measurement points causes major technical problems related to the workload, and the huge volume of data acquired and processed. The possibilities of making the 3D model available in digital space for the purpose of researching the appearance and geometry of the mosque, its individual columns, as well as popularising the monument are also discussed. It is highly probable that the scanning of the Juma Mosque's interior presented here was carried out for the first time in history.

Keywords Information technologies, Laser 3D scanning, Historical buildings, Mosque, Deeply carved wooden columns

Introduction

Digitisation of material cultural heritage monuments is a modern method of identifying, protecting, conserving, restoring, and passing to future generations data concerning cultural heritage monuments. Monument protection concerns the following areas [1]:

- documentation,
- protection,
- reconstruction,
- renovation,
- conservation,
- dissemination,
- popularisation.

Many of the above activities can be supported by information technologies (IT). They can be used primarily for documentation [2–5], dissemination [6–8] and popularisation [9, 10], but they are also helpful during the renovation and reconstruction [11, 12] of lost monuments or their protection, including digital preservation [13, 14]. The requirement is to obtain a digital 3D copy of

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the monument. Digital copies of monuments (so-called digital twins) can be stored long-term (one might say for ever) at low costs and used many times for various purposes. An example of this is the use of 3D scans in the reconstruction of the Cathedral of Notre-Dame de Paris (France) after its fire in 2019 [15].

The article briefly presents the authors' previous experience in 3D scanning of large architectural objects in the domain of the human cultural heritage, located on the Silk Road in Central Asia (mainly in today's Uzbekistan). The focus of the study is a particular building that the team encountered during one of the Scientific Expeditions of the Lublin University of Technology to Central Asia, namely the Juma Mosque in Khiva (Uzbekistan). It stood out from other architectural structures scanned in Central Asia because of a very large number of spatial details and its complex geometry. This characteristic of the object created specific problems in the course of in situ data acquisition and their subsequent processing, which are presented in the article, as well as their solutions implemented by the authors. The final part of the work summarises the possibilities of making the 3D model available in digital space for the purposes of researching the appearance and geometry of the mosque's interior, its individual columns, as well as popularising the monument.

Study background

Since 2015 scientists from the Lublin University of Technology, together with colleagues from universities and museums in Uzbekistan, have been carrying out research involving the use of 3D IT techniques in the area of cultural heritage. Most of the work was done during the project "3D Digital Silk Road" funded by the Polish National Agency for Academic Exchange (NAWA) (www.nawa.gov.pl). The project results are presented on the web portal 3D Digital Silk Road [16].

During the eight previous Scientific Expeditions of Lublin University of Technology to Central Asia, historic buildings and museum artefacts were scanned, such as:

- Golden Mosque of the Tillya-Kori Madrasah in Samarkand [17],
- huge buildings of Muslim universities (e.g. Ulugh-Beg Madrasa in the Registan complex in Samarkand) and mausoleums (e.g. Gur-e-Amir Mausoleum) [18],
- valuable museum robes of the rulers of Bukhara [19],
- ceramic vessels from 2000 years ago [20], and even
- petroglyphs [21], or
- folk dances [22].

Most large architectural objects were scanned under normal tourist traffic conditions. For such conditions, a special methodology has been developed and repeatedly tested in practice: 3DScaMITE— the 3D Scanning Methodology in Intensive Tourism Environment [18].

Stationary laser scanners—Terain Laser Scanners (TLS)—were used to scan large architectural objects (but also e.g. petroglyphs) during the Scientific Expeditions of Lublin University of Technology to Central Asia. These were FARO Focus X 330 and S 350 + scanners. These scanners work autonomously—data are saved to the built-in memory and/or to a memory card. These scanners have built-in high-resolution digital cameras to capture the appearance (texture) of surfaces. They also have a whole set of additional sensors such as GPS, digital compass, altimeter (GPS and atmospheric) and inclinometer. The newer scanner (FARO Focus S 350 +) has a distance measurement range of up to 350 m, with a systematic error (accuracy) of ± 1 mm (and a random error of 0.3–0.5 mm), measurement speed (point acquisition) up to 2 million points per second. The camera module of this scanner has HDR (High Dynamic Range) function and a 165 million pixels colour matrix. The scanner measures 360 degrees horizontally and 300 degrees vertically. The scanner weighs about 4.2 kg and works on one battery for up to 4.5 h. Having a spare battery allows to scan for up to 9 h a day without charging, and about 11–12 h with recharging one battery while working on the other one. An important parameter of the scanner is the capacity of its battery, which is 97.2 Wh. The battery therefore meets airline standards for trouble-free transportation on passenger planes in hand luggage.

The huge buildings of mosques, mausoleums and madrasas in Uzbekistan, despite their very large sizes (for example: the area of Ulugh-Beg Madrasa from the fifteenth century is 56 × 81 m, and the height of the façade arch is 32 m) and wonderful mosaic decorations, have relatively simple geometry—Fig. 1. Simple geometry means that the scanning process requires a relatively small number (usually: 5–10) of scanner setup points (measurement positions) to cover the entire building or interior. As a consequence, the time spent on data acquisition (and their volume) is not very large, even with a large number of measurement points per cm^2 (resolution of 20–50 points per 1 cm^2). The total scanning time was usually 2–3 h, resulting in the acquisition of over 30–100 million measurement points and approximately 1–3 GB of raw data stored by FARO scanner (including photos taken by the scanner's camera).

During the 6th Scientific Expedition of the Lublin University of Technology to Central Asia in 2021 (https://cs.pollub.pl/6-wyprawa-naukowa-politechniki-lubelskiej-do-centralnej-azji-etap-2/?lang=en) an attempt was made to scan the interior of the Juma Mosque located in the old city centre of Khiva (Uzbekistan), surrounded

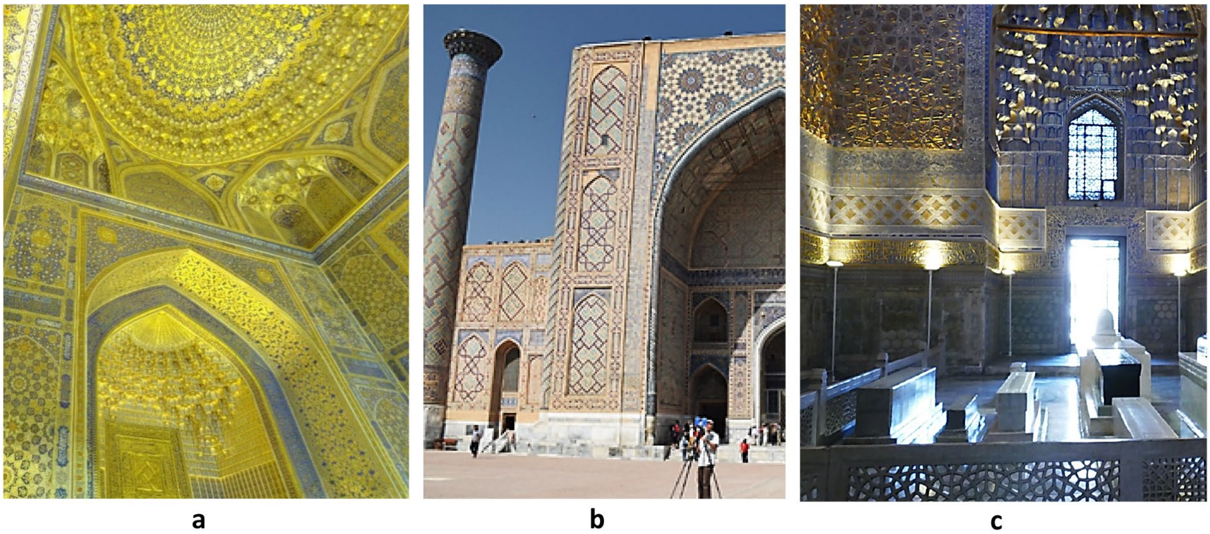


Fig. 1 Appearance of: **a** the interior of the Golden Mosque, **b** the front of the Ulugh-Beg Madrasa and **c** the interior of the Gur-E-Amir Mausoleum (all sites in Samarkand, Uzbekistan)

by a defensive wall, called Itchan Kala (meaning: Inner City). The interior of the Juma Mosque, with dimensions of 55×46 m, comparable to typical madrasa courtyards, turned out to be quite a challenge. The interior hides a large number of details in the form of 213 richly carved wooden columns (each different and from a different period). As a result, problems arose in terms of spatial (i.e. determining the scanner placement positions) and temporal planning of the 3D scanning procedure as well as the subsequent processing of the acquired data. Preliminary calculations indicated the need to perform at least 250 scans (and maybe even over 500 with two different scanner height settings above the floor), which is on average 25–50 times more than in the case of "typical" very large, but geometrically simple (similar to the interior of a cube with a small number of cavities), architectural objects scanned so far in Central Asia during the Lublin University of Technology's expeditions to Central Asia. These 250 scans would take over 50 h of work (counting 12 min for one scan). A separate problem would be the volume of the collected data, making it difficult, if not impossible, to process the entire scanning area without access to an expensive high-end computing system.

Therefore, the following research thesis was formulated:

> ***It is reasonable to obtain data during TLS with the best possible accuracy (technical and organizational), even if it will not be possible to fully use it nowadays. The current advancement in the computing hardware and software is fast enough to provide such availability even within the project span.***

In order to confirm (or disprove) the defined research thesis, a highly detailed historical architectural object (i.e. the Juma Mosque in Khiva) was scanned and the data obtained as a result were processed.

Methods and materials

Juma Mosque as a highly detailed historical building

Ichan Kala is the inner part of the city of Khiva, surrounded by defensive walls. It is included in the UNESCO World Material Heritage List [23]. The city of Khiva is located in what is now Uzbekistan in Central Asia on the ancient Silk Road and was founded over 2500 years ago [24]. The city was completely destroyed in the early thirteenth century by the troops of Genghis Khan, but flourished in the fourteenth century under the rule of the Timurids. From the sixteenth century, Khiva was the capital of the khanate until its liquidation by Russia in the nineteenth century [25]. After the twists and turns of twentieth century history, including the actions of the Soviet Union, Khiva eventually became part of an independent Uzbekistan, as the capital of the semi-autonomous region of Karakalpakstan [26].

The Juma Mosque is located in Ichan Kala (Uzbek for "inner city")—Fig. 2. It is one of the most famous medieval buildings in Khiva and throughout Central Asia [27]. It differs from other mosques in its original design (unlike e.g. Timurid mosques) and size, without portals, internal courtyards or huge brick domes.

The Juma Mosque was first mentioned by the Arab traveller Al-Maqsudi, who came to Khorezm in the tenth century. According to historical records, the Juma

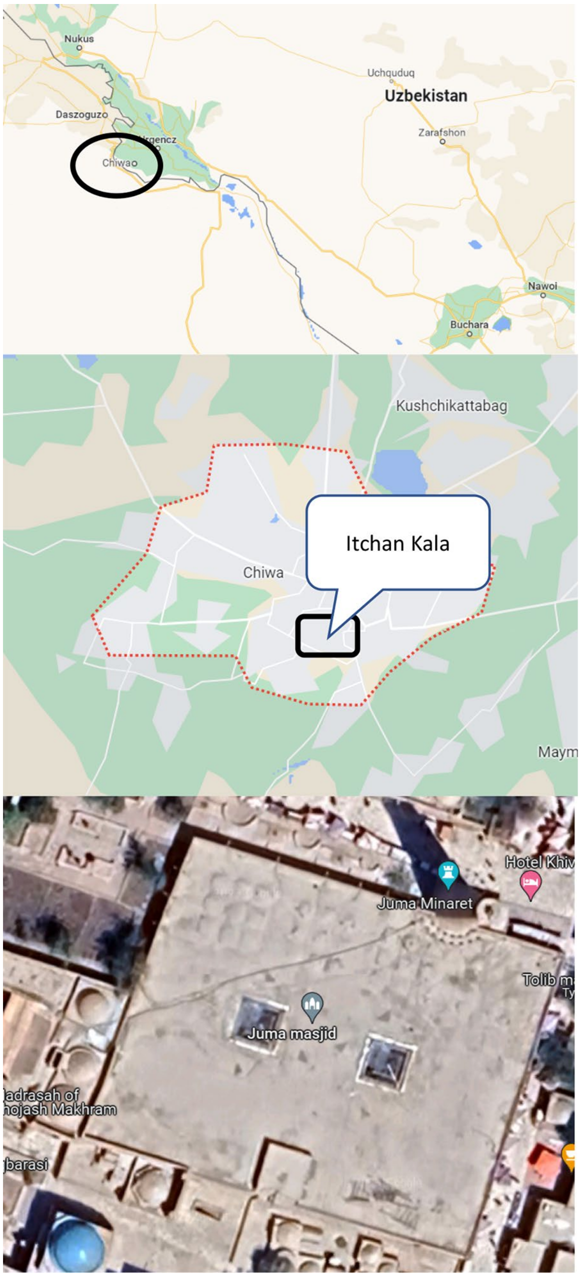


Fig. 2 Location of Khiva, Itchan Kala and Juma Mosque. Source: https://www.google.com/maps

Mosque was destroyed in 1788 [28] and rebuilt in later years following the same plan.

The shape of the mosque building is very simple. It was built on a rectangular plan with the dimensions of 55 × 46 m, and the height of its only minaret (Fig. 2) is 42 m. The height of the mosque's outer walls is approximately 4.5 m. Inside there are 213 columns supporting a flat roof. The columns are placed on a square grid of ~ 3.15 m on sides (Fig. 3a). In addition, the mosque also has a minbar or pulpit (Fig. 3b) and a small marble dome with a water container for praying (Fig. 3c). The interior is illuminated by two roof windows. Currently, mini gardens with green plants have been organised under the roof windows. In December 2020, a team of scientists from the University of California, Berkeley (USA) and the Urgench State University, Urgench (Uzbekistan) carried out 3D scanning of the exterior and surroundings of the mosque in order to build a numerical model of the minaret and use it to study the impact of vibrations on the condition of the minaret [29, 30]. However, there is no trace of information whether an attempt was made to 3D scan the interior of the Juma Mosque. This information is also missing from the available literature. It is highly probable that the team from the Lublin University of Technology (Poland) was the first in history to do this in a methodical way.

The columns supporting the ceiling of the mosque, together with the lower stone pedestals, have shapes typical of the Central Asian culture (Fig. 4). The columns have an extended pear-like shape, with a significant narrowing at the bottom, which fits into the stone plinth. The plinths have different shapes, but a similar upper structure, which serves as a socket for the column. These columns are (especially in their lower part, but not only) richly carved (Fig. 5). The columns support the nodes of the flat wooden ceiling using various structures (Fig. 6). They come from different periods. The 25 oldest columns were made in the tenth-fifteenth centuries [31].

Each wooden column has its own unique dimensions (they even differ in height, levelled by a stone plinth) and decorations made by deep wood carving. The patterns are not very large (characteristic of hand carvings) and there are a huge number of them. Due to the large number of columns and the complexity of their decorations, the Juma Mosque can be called a highly detailed and geometrically complex historical architectural object.

Method of scanning and its optimisation

3D scanning was carried out without the mosque being closed to tourists, i.e. during normal tourist traffic. The scanning process used the 3D Scanning Methodology in Intensive Tourism Environment (3DScaMITE) [18] developed and repeatedly verified in practice. This methodology was modified by adding a new task called "Optimisation of the Scanning Process" in the "Planning" stage.

The initial planning to scan 213 columns in the Juma Mosque, assuming each column was scanned separately from four sides to achieve adequate accuracy, resulted in approximately 1000 scanning positions (although one scan position can be used for four neighbouring columns lowering the number to around 250). Planning two or

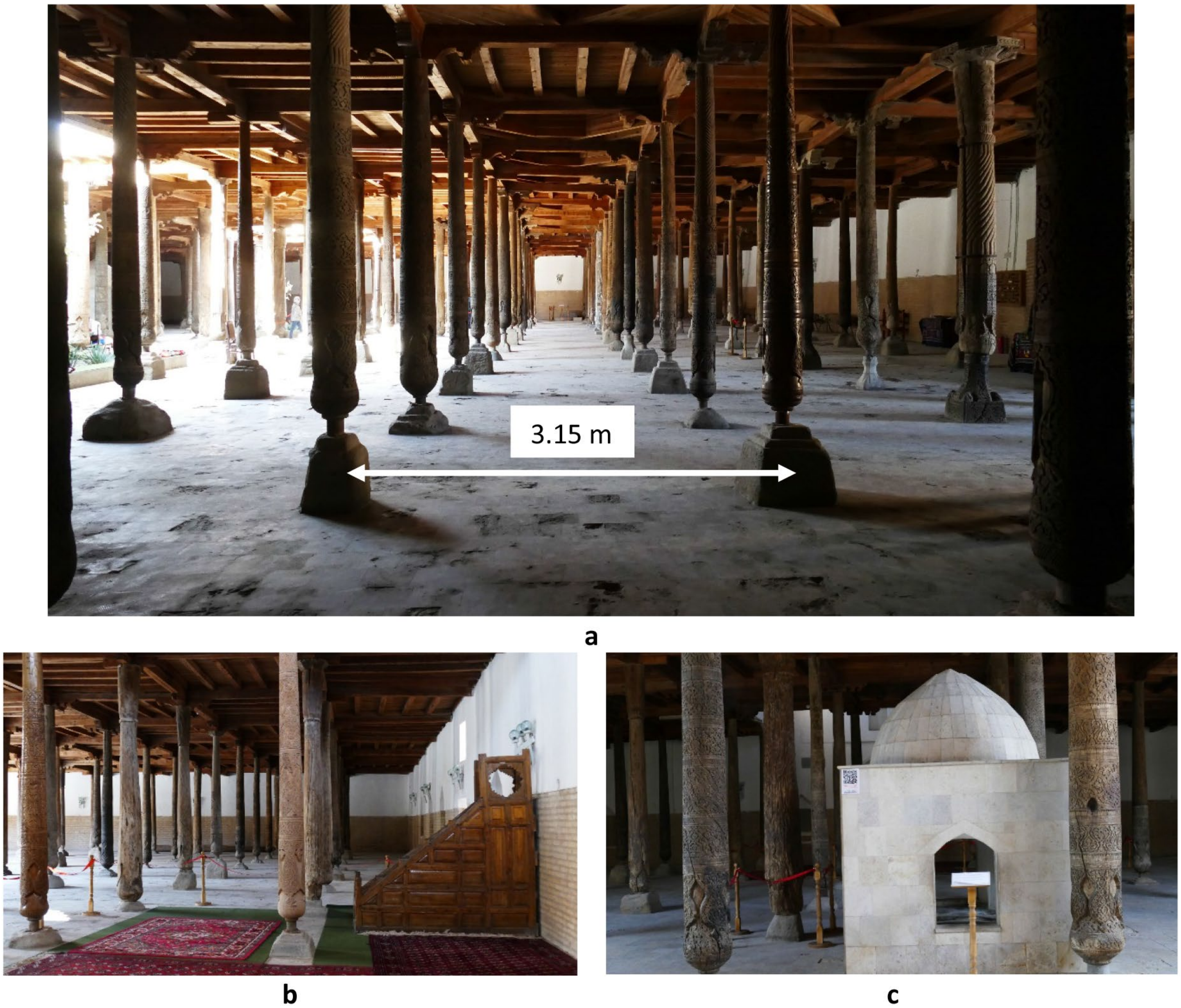


Fig. 3 General appearance of the interior of the Juma Mosque: **a** arrangement of columns, **b** minbar, **c** small marble dome

more scanner positions above the mosque floor multiplied the number of scanning points.

Due to the shape of the columns, it was possible to find one position of the scanner that made it suitable to perform a correct scan for the entire column—Fig. 7.

Taking into account the regular square grid of columns, it was possible to plan the arrangement of the scanner in the centres of squares (a scan cell) with vertices determined by the geometric centres of the columns. In this position, the scanner simultaneously scanned four columns from one position (Fig. 8). This allowed us to reduce the number of scans by approximately four times, i.e. to approximately 250.

Taking further advantage of the regularity of the column arrangement, it was decided to further reduce the number of scanning points, retaining every second one. The spacing of the scanning points was determined according to the principle of positioning the scanner in a scan cell that does not border by the edge with another scan cell chosen for scanner placement (Fig. 8c). In this way, the missing data about the column area is supplemented as a side effect by further scanning positions (blue). This reduced the number of scanning positions to 128, which was feasible within the time available. This number of scanning positions is still much higher than the typical number of 5–10 scans for "simple" architectural objects.

These actions allowed us to plan the scanning positions as in Fig. 9 (red crosses), condensing them slightly around the small marble dome due to its geometry.

Scanning implementation

The scanning process was carried out in two-person teams, periodically replaced due to the low air temperature inside the mosque. One person was responsible for moving the scanner and conducting the scan. The second

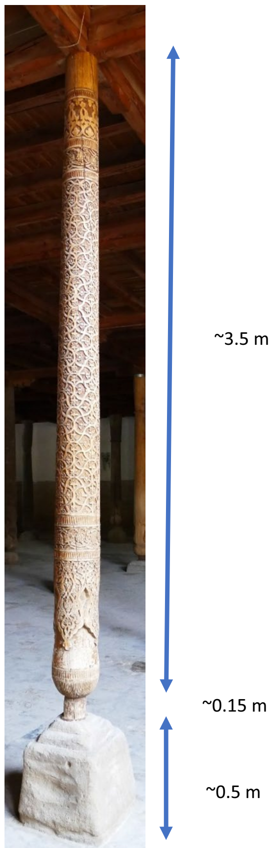


Fig. 4 Typical shape and dimensions of a column in the Juma Mosque

person designated the location of the scanner and kept the handwritten documentation. The scanner was placed according to the optimised plan near the centre of the square defined by the four columns (Fig. 10). There was no need to determine this exact position using geometric methods. Due to the diversity of shapes of wooden columns and their stone bases, it was practically impossible to determine the exact location of the centre of the square, the vertices of which were the geometric centres of the columns. The location of the scanner low above the ground was related to the shape and sculpture of the columns with rounded bases.

Due to tourist traffic, some scans had to be repeated. Such problems occurred during visits by a large number of people, i.e. organised trips. The tours stopped long enough to listen to the guide's explanations, which introduced gaps in the scans due to long-term obscuration of the scanned columns.

Another problem related to the long scanning time was the change in lighting. The interior of the mosque has no artificial lighting. It is illuminated by two roof windows. During the scanning process, the sun moved and was obscured by clouds, which caused changes in the lighting inside the mosque. These changes were partially eliminated by a procedure built into the FARO Focus S 350+scanner used. At the end of the scanning process, the camera measures the lighting of each position and adjusts the parameters of photographs, taking all environmental conditions into account. The lighting differences have no effect on laser scanning accuracy, it only

Fig. 5 The carved lower parts of the columns in the Juma Mosque (examples of the appearance of columns from different periods)

Fig. 6 The upper parts of the columns supporting the nodes of the wooden ceiling of the Juma Mosque

Fig. 7 Height of the scanner above the floor level ensuring correct scans

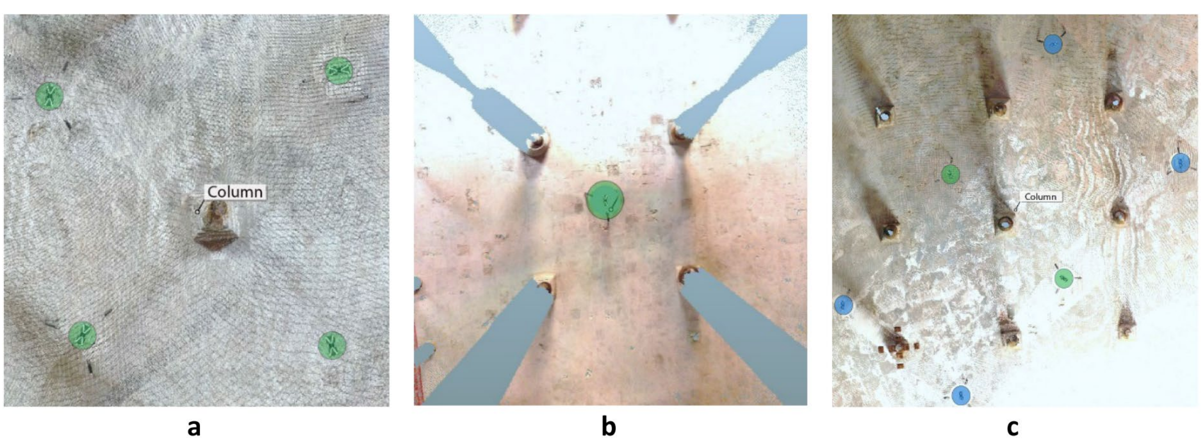


Fig. 8 Scanner placement positions: **a** four scans per column, **b** one scan simultaneously for four different columns, **c** minimum number of 6 scanner positions to obtain visibility of the entire surface of the column (Column) (green—close position and blue—further position markings are scanner placements)

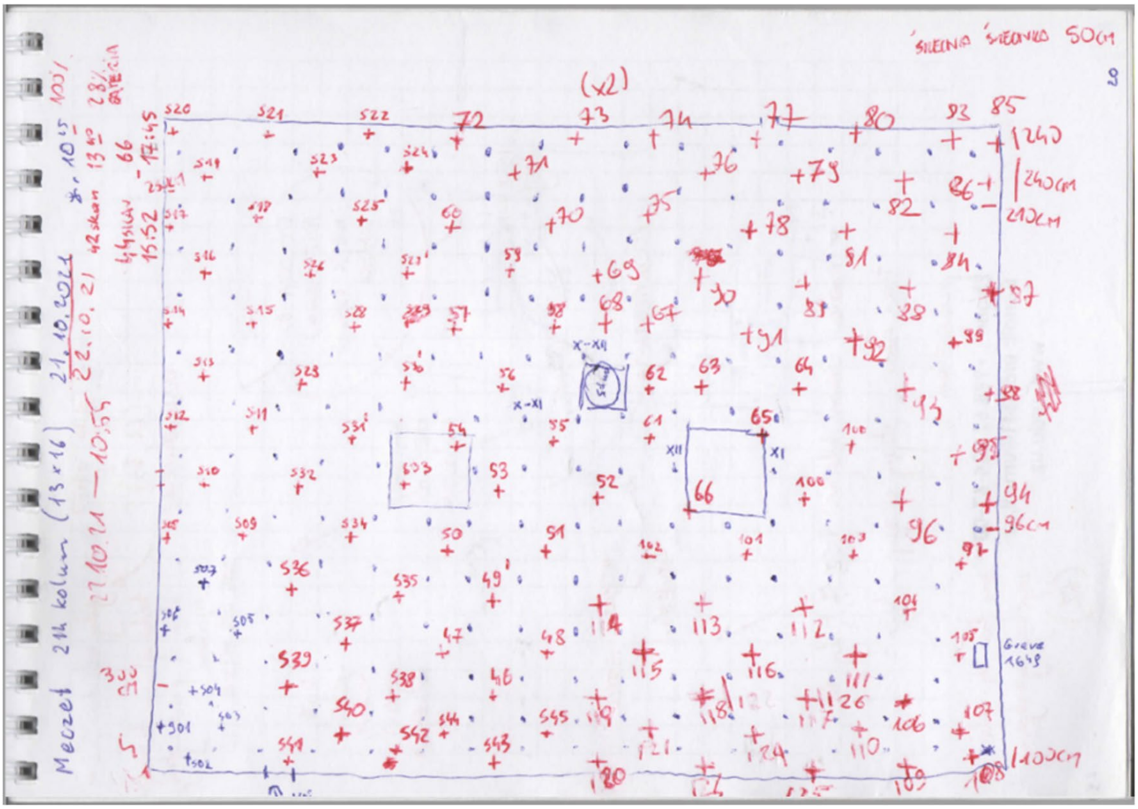


Fig. 9 The appearance of the handwritten scanning plan (blue dots represent columns and red crosses—scanning positions) and its implementation (red numbers with possible repetitions)

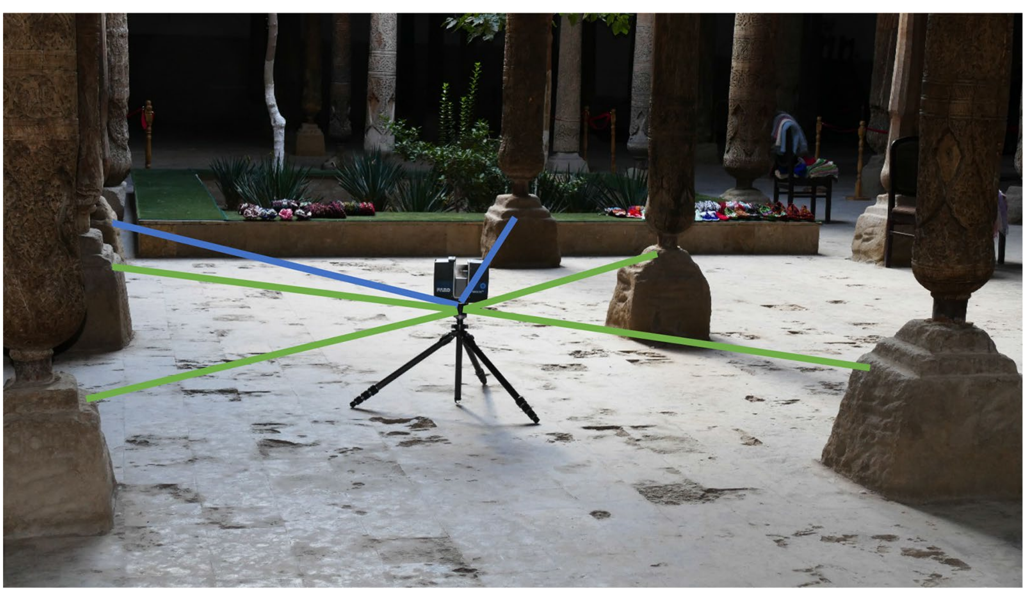


Fig. 10 Scanning the interior of the mosque from the centre of the square between the columns. Indicated are columns in the near range (green) and far range (blue) for this scanner position

makes it difficult to generate an uniform texture for the acquired 3D model.

Results

Obtained results about Juma Mosque

Despite the in-situ optimisation of the scanner placement positions, the scanning time was almost 14 h (two working days), over 27 GB of raw data was acquired (from 126 scans), and the resulting point cloud (after combining partial clouds) amounted to almost 2.1 billion (i.e. 2,100 million) points (Fig. 10). These sizes are several times larger than typical large objects from Central Asia. This resulted in the inability of building a base 3D mesh model of the mosque in 2021. The dedicated scanner software enabled the generation of a 3D mesh containing a maximum of 2 million triangles, which was definitely too small to make the grooves on the columns visible.

The possibility of generating appropriately detailed 3D meshes (software and hardware) appeared only in 2023. The Reality Capture software and an appropriately efficient workstation were acquired (64-core processor, 512GB RAM, high efficient RTX 4090 graphics card). This allowed us to generate a model with an average detail of 1 million triangles per column.

Data postprocessing

The initial processing of data from 128 scan positions consisted of typical operations: import and colorization of scans and registration. Matching the scans, although time-consuming, was carried out without significant difficulties due to the easy positioning of each scan (walls, floor and ceiling visible)-(Fig. 11). The obtained Mean Point error, i.e. the inaccuracy of matching the scans, below 2 mm is satisfactory. As a result, the intermediate project contained ~ 350 GB of pre-processed data.

The next stage included the elimination of undesirable points registered as a result of intense tourist traffic during scanning—Fig. 12. Some situations were eliminated during the scanning process: the scan was interrupted (and sometimes deleted) and repeated. Arranging columns in rows made it easier to define areas "to be cleaned". Despite this, it was the most time consuming part of data processing, carried out manually.

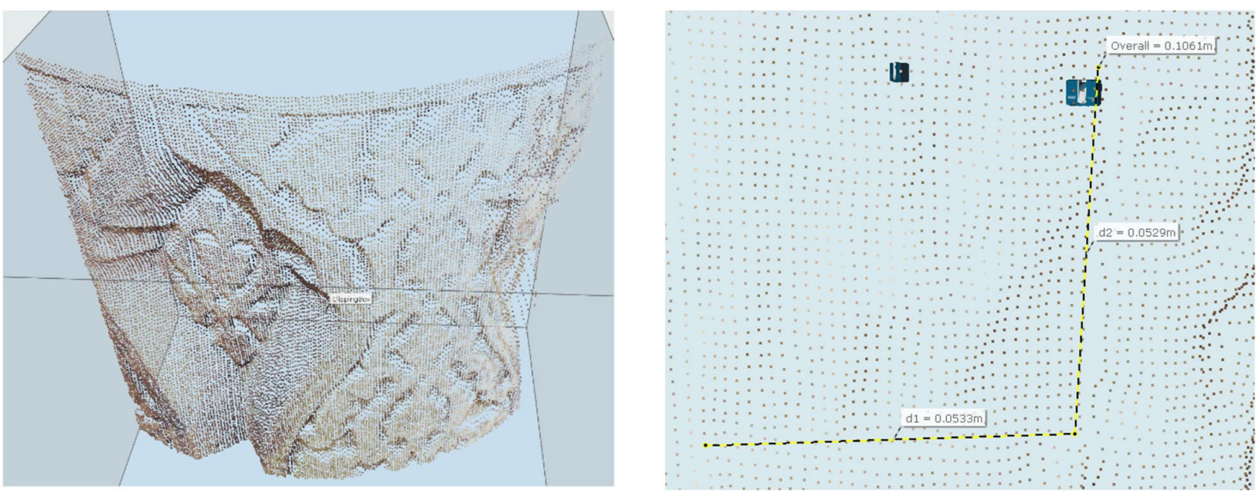
The final result was the acquisition of a point cloud depicting the interior of the Juma Mosque containing over 2.1 billion points. The average cloud density for the column surfaces, i.e. the areas with the greatest detail, was 20 points/cm^2 (Fig. 13).

This allows for the construction of a 3D mesh for any column with a resolution revealing the unique shape of the carvings (Fig. 14). Such mesh models, after appropriate further processing, can be used to print columns or their fragments on a reduced scale on 3D printers (Fig. 15), or even make copies of them in a 1:1 scale on appropriate numerically controlled (CNC—Computerized Numerical Control) machines working in wood or other material. Prints can be used to create museum exhibitions, and copies—to reconstruct a column after its destruction (e.g. as a result of fire or pest activity [32]).

The base (full) 3D point cloud model of the Juma Mosque, despite its large volume (approximately 55 GB) is available on the Lab3D server of the Department of Computer Science of the Lublin University of Technology (Lublin, Poland). It can be viewed in the web browser (via the free Potree viewer) under address: https://silkroad3d.com/juma/ (accessed 25 February 2024). It will also be provided for the research purposes, upon request sent to the authors of this article. When the availability arises it will be transferred to publicly available repositories, such as the European Collaborative Cloud on Cultural

Fig. 11 An overview of the combined point cloud from the Juma Mosque scanning with scanning positions (marked with a blue scanner hardware shape between the columns). Some of them are duplicates

Fig. 12 An example of interference in the acquired scans



a b

Fig. 13 Presentation of the point cloud density in the column area: **a** overview of a fragment of the column, **b** the cloud density in respect to width (d1) and height (d2) dimensions

Heritage to be created under the Horizon Europe Fund [33], allowing access and examination of the acquired source data by a wide community of cultural heritage researchers and institutions.

Problems and its solutions

Many problems were identified and dealt with during scanning and processing of the data.

Problem 1. The object contained a significant number of elements (columns) with complex shapes that required careful scanning.

The typical accuracy of scanning building interiors using TLS does not require the registration of all surfaces with the maximum available accuracy (flat surfaces such as walls can be mapped based on a lower density of measurements). The need to maintain high resolution as well as the mutual obscuration of the

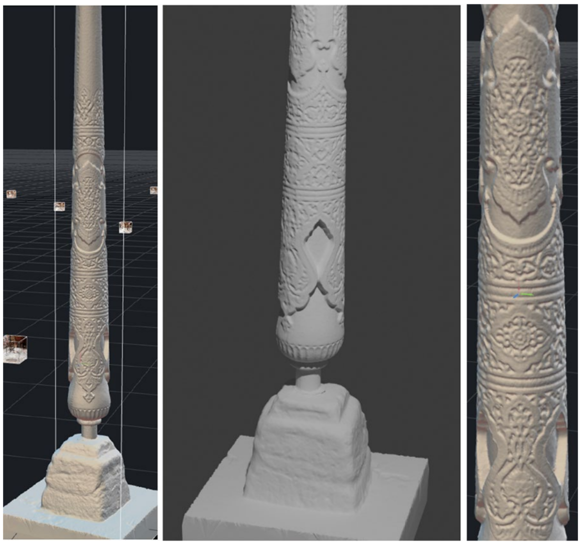


Fig. 14 3D mesh model views of a column from the Juma Mosque

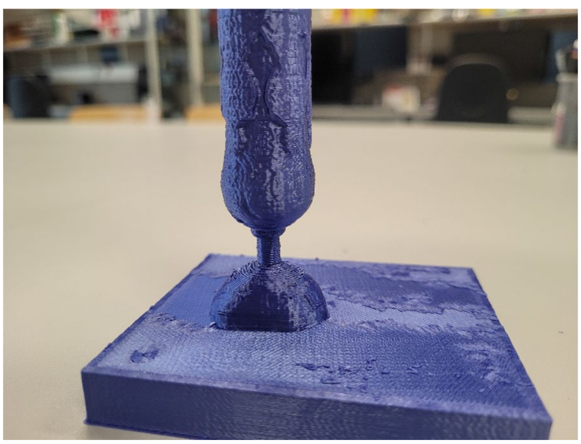


Fig. 15 3D print of a fragment of a column from the Juma Mosque

columns forced a significant increase in the number of necessary scanner positions.

The scanner had to be placed at a relatively short distance from the object (no further than 10 m, a distance where the basic scanner accuracy of + -1 mm is guaranteed). The cylindrical shape of the column necessitated scanning from at least 4 positions around it. The number of scans for all columns would be significantly greater than could be completed in the available time of two business days. Additionally, the volume of data collected would likely exceed the processing capabilities of the scanner software.

The solution was to optimise the scanning position presented in the chapter: "Method of scanning and its optimisation". This allowed the task to be completed within the available time and preliminary data processing using the equipment available at that time.

Problem 2. Limited scanning execution time.

Despite the optimisation used, the number of scans was still high. Therefore, it was impossible to repeat scans in a given position at different scanner heights. The standard scanning height (corresponding to human height) at a scanner distance of several meters from the column offers good coverage of the groove surfaces, but introduces the risk of not scanning the rounded bottom of the column (often richly carved) located below the scanner (Fig. 4). Optimal scanning would require two scanner height positions at one scanning position.

It was decided to lower the position of the scanner to approximately 50 cm above the ground and resign scanning from other heights. In this position, the scanner covers both the bottom of the column and the grooves above it. The disadvantage of this arrangement is the sharper angle at which the laser scans the upper part of the column, which introduces larger losses in the scan of the bottom of the grooves. This may lead to distortions in the gouge reconstruction (Fig. 16).

The above decision was made due to the fact that the vast majority of the columns are smooth at the top, i.e. without grooves. Potential distortions will therefore occur in a small number of cases.

Problem 3. The scanning conditions negotiated with local authorities did not include exclusive access to the scanned object.

Unfortunately, a common situation encountered by the team carrying out the described project of scanning large cultural heritage objects is the lack of consent from local authorities to close the object for the duration of the scanning, which would ensure uninterrupted data collection. Given the choice of scanning during tourist traffic or not scanning at all, the authors of the article developed the previously described the 3DScaMITE procedure [18], which allows for minimising disruptions caused by tourist traffic in such cases.

This procedure was successfully used in the described case, although the stage of cleaning the scans turned out to be more time-consuming due to the unusually large number of them.

Problem 4. The volume of collected data significantly exceeds the volume of data for this type of objects

At the time of scanning (i.e. year 2021), the software and hardware resources available only allowed for the initial processing of such a complex project. A typical feature of this type of scanning data collection is the

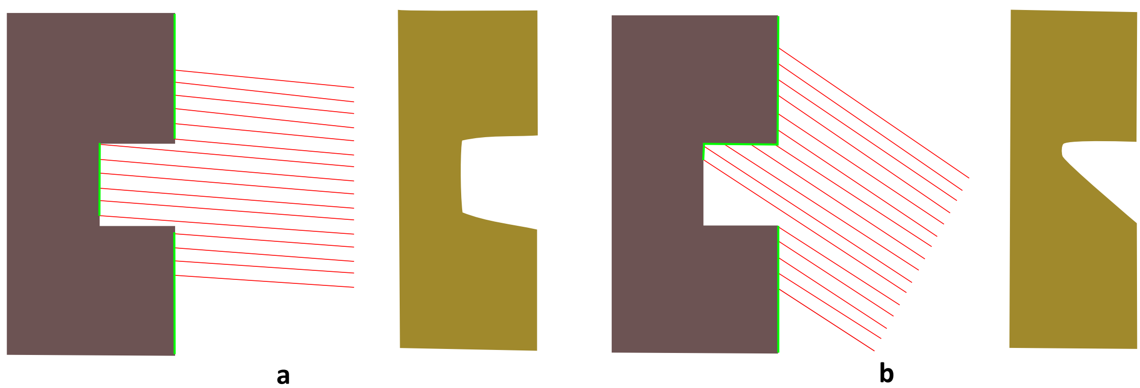


Fig. 16 A probable reconstruction of the column carving when the laser beam (red lines) enters the carving at: **a** flat angle, **b** acute angle (On the left side of Fig. a and b there are scanned objects, and on the right side—reconstructed objects. The green lines mark the column surface visible for the scanner)

permanent preservation of source data and the ability to return to its processing as new software and hardware resources are acquired.

The Reality Capture software, acquired in 2023, allows to import a large number of scans and generate a model of the object in the form of a mesh of triangles numbering in billions. This is accuracy high enough to reproduce the grooves in all 213 columns.

Currently available workstations with processors with 64 or more cores and an operating memory counted in TB and very efficient graphics systems allow for the acquisition and further processing of such complex mesh models within a period of time (several dozen hours) allowing for free testing of parameters to obtain the optimal result.

To summarise it has been proven that the above-mentioned problems are obstacles that can be overcome with current state of the art in the area of 3D scanning. The 3DScaMITE methodology was once again [18, 34] successfully implemented in very difficult conditions of a complex architectural building.

Discussion

Despite a number of organisational and technical problems occurring during the work, it was possible to scan with the best possible accuracy (technical and organizational) the interior of the Juma Mosque despite its highly detailed and geometrically complex nature. The problems were solved by:

- optimisation of the scanning process (scanner position and number of scans) while maintaining the highest accuracy for the scanner;
- application of the 3DScaMITE methodology enabling scanning during normal tourist traffic;
- acquiring new software (i.e. Reality Capture) and powerful workstations for data processing during post-processing (only 2 years after scanning).

Consequently, the research thesis: "***It is reasonable to obtain data during TLS with the best possible accuracy (technical and organizational), even if it will not be possible to fully use it nowadays. The current advancement in the computing hardware and software is fast enough to provide such availability even within the project span.***" has been CONFIRMED.

Conclusions

Research on a specific example of a highly detailed and geometrically complex historical architectural object allowed us to prove that it is possible to implement with the current state of technology and with very high accuracy, of the order of 20 measurement points per cm^2. Moreover, the case study showed that despite the current lack of technical possibilities for post-processing of the acquired data, such possibilities may appear in the near future. Therefore, it is worth obtaining data from objects with the highest possible accuracy and storing them in raw form.

The base model can be used for scientific research, including:

- carrying out accurate measurements of the interior geometry of the mosque;
- historical and other research on the appearance of individual columns in the mosque;
- detecting decorative patterns of columns in different periods without research *in-situ*, also using the Artificial Intelligence (AI) methods;

- implementation of exhibitions of physical 3D copies of column models, including exhibitions for the blind with the possibility of visiting them using the sense of touch;
- creating Virtual Reality (VR) models of the mosque and researching their use to optimise mosque tours;
- research on changes in the geometry of the mosque and its columns (this is possible after re-scanning the interior of the mosque and comparing it with data obtained in 2021).

In addition to research work, the base 3D model of the mosque can be the basis for generating simplified models for sharing over the Internet, 3D panoramas—for the same purpose, and files for VR devices. These elements can be used to widely popularise the appearance of the mosque. Work on these solutions is ongoing.

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Author contributions
Marek Milosz conceived and designed the experiments, performed the experiments, analysed the data, authored or reviewed drafts of the paper, and approved the final draft. Jacek Kęsik performed the experiments, processed the scanned data, prepared figures and approved the final design. Utkir Abdullaev designed the experiments, performed the experiments, reviewed drafts of the paper and approved the final design.

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Availability of data and materials
The base (full) 3D point cloud model of the Juma Mosque, despite its large volume (approximately 55 GB), is available on the Lab3D server of the Department of Computer Science of the Lublin University of Technology (Lublin, Poland). It can be viewed in the web browser (via the free Potree viewer) under address: https://silkroad3d.com/juma/ (accessed 25 February 2024). It will also be provided for the research purposes, upon request sent to the authors of this article.

Declarations

Competing interests
The authors declare there are no competing interests.

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