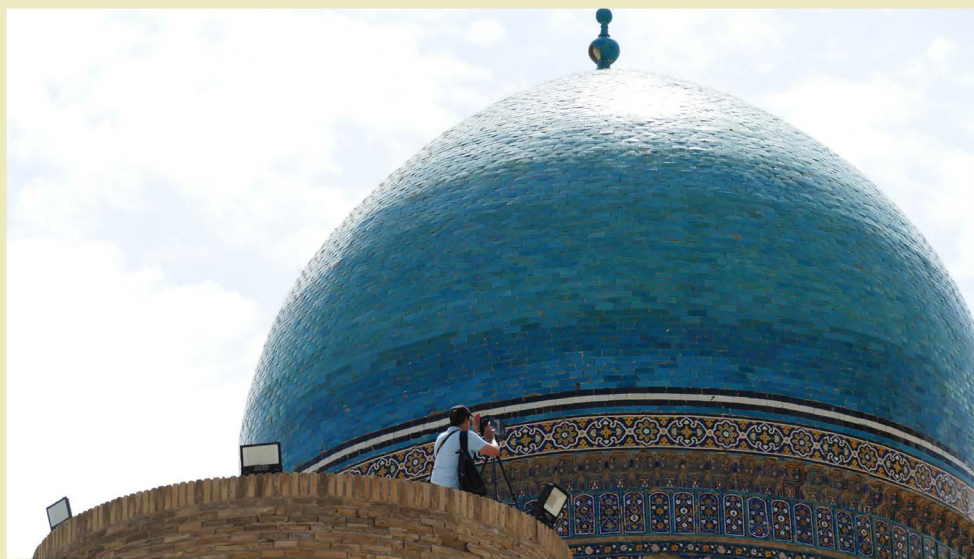




*Marek Miłosz
Jerzy Montusiewicz
Jacek Kęsik*

3D Information Technology in the Protection and Popularization of the Cultural Heritage of the Silk Road



MONOGRAPHIE

3D Information Technology in the Protection and Popularization of the Cultural Heritage of the Silk Road

Monografie – Politechnika Lubelska



POLITECHNIKA
LUBELSKA
WYDZIAŁ ELEKTROTECHNIKI
I INFORMATYKI

Marek Miłośz
Jerzy Montusiewicz
Jacek Kęsik

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Lublin 2022

Reviewers:

Prof. Sergio Luján Mora, University of Alicante, Spain

Prof. Anatoliy Sagdullayevich Sagdullaev, National University of Uzbekistan named after Mirzo Ulugbek, Academician of the Academy of Sciences of the Republic of Uzbekistan, Uzbekistan

Authors:

Marek Miłośz, Ph.D., Eng., Prof. LUT, Lublin University of Technology

Jerzy Montusiewicz, D.Sc., Eng., Prof. LUT, Lublin University of Technology

Jacek Kęsik, Ph.D., Eng., Lublin University of Technology

Cover photo: Elżbieta Miłośz

Linguistic proofreading: Jerzy Warakomski

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Introduction

The Great Silk Road with a length of about 12,000 km is a historical and geographical space stretching from China in the east, through the countries of Central Asia, to Europe in the west. This route was used by thousands of caravans to transport goods for almost 2,000 years from the turn of the 3rd/2nd century BC until the mid-17th century AD (discovery of the sea route to China). The exchange of goods contributed to the economic development of many states and regions, in the European context it was primarily the Byzantine Empire, but also the city-states of Italy. The many routes stretching from east to west were also joined by trails from the south, including those from India, Pakistan, Afghanistan or Iran.

Ancient monuments lying on the Silk Road are: cities, fortresses, mosques, madrasahs, as well as their ruins and various types of artefacts (ceramic and bronze objects, jewelry, weapons, sculptures and frescoes) found in numerous archaeological excavations have for centuries been of interest to travellers, historians, art historians, archaeologists or museologists. The many years of their activities have contributed to the preservation of this heritage, the reconstruction and conservation of individual architectural structures, making them available for visiting by the local population, but also for tourists coming from all over the world. In this situation, it may come as a surprise that the employees of the Department of Computer Science of the Lublin University of Technology also work on the Silk Road. Many simple questions are on the lips: why, for what purpose, what are they doing there, is it just a tourist trip, or maybe a research expedition.

The history of these trips isn't long, but has two equally important components that happened simultaneously in 2015. The first concerns the organisation by Prof. Jerzy Montusiewicz of a specialised unit: Laboratory of Intelligent Systems Programming and Computer 3D Technology ("Lab 3D"), which gathers hardware, software and a competent team for creating digital 3D models of large and small objects of tangible material heritage, as well as their 3D printing and sharing in many different ways. The second is the acquaintance by Prof. Marek Miłosz and his wife, Dr Elżbieta Miłosz, during their stay in Samarkand (Uzbekistan), of Rahim Kayumov, a museologist, head of the Science and Practice Museum-Laboratory belonging to the Samarkand State University.

The cooperation has had an interdisciplinary character, which means that both parties bring to it knowledge and skills that are unique. This situation has built mutual respect between the partners and, through the generated synergy, allowed for the achievement of exceptional results. The partners from Uzbekistan and Central Asia represented specialist knowledge in the field of history and art history. They also ensured access to a variety of material culture goods, on which we could work with our skills. Employees representing "Lab 3D" from Lublin University of Technology (LUT) dealt with 3D digitisation of cultural heritage objects using both laser scanners and structured light in situ technology. In Lublin, they processed the obtained data, generating digital 3D models of various quality and properties. These models were suitable both for archiving purposes, sharing on websites, generating walks

in the world of Virtual Reality and creating interactive panoramas of omnidirectional or three-dimensional printouts.

Three periods can be distinguished in the cooperation between Lublin and Samarkand.

The first period – 2015–2016, was a distance cooperation during which both the first publications and documents on formal cooperation between our universities were created.

The second period – the years 2017–2019, are the years of the first three Scientific Expeditions of the Lublin University of Technology's employees of the Department of Computer Sciences (Prof. Jerzy Montusiewicz, Prof. Marek Miłosz and Dr Jacek Kęsik) to Central Asia. The area of our activities covered both Uzbekistan, Kazakhstan and Kyrgyzstan. Partners from Central Asian countries also visited Poland. Two scientific conferences were organized together: International Conferences on Information Technology in Cultural Heritage Management (2018 in Lublin, Poland, and in 2019 in Samarkand, Uzbekistan). Joint research and publications were also created, as well as the portal "3D Digital Silk Road, silkroad3d.com".

The third period – 2020–2022, is the implementation of the "3D Digital Silk Road" (PPI/APM/2019/1/00004) project financed by the National Agency for Academic Exchange. The existing cooperation has been extended to three new universities in Uzbekistan: National University of Uzbekistan, Chirchik State Pedagogical Institute of Tashkent Region and Urgench State University. The initial duration of the project coincided with the coronavirus pandemic, which significantly limited activities, but despite this, a virtual conference was organised, which resulted in the publication of two monographs (*Tangible Cultural Heritage of the Silk Road from the Area of Modern Uzbekistan* and *Intangible Cultural Heritage of the Silk Road from the Area of Modern Uzbekistan*). In addition, a virtual Scientific Expedition of the Lublin University of Technology to Central Asia was organised, thanks to which two collections of digital 3D models were prepared (https://silkroad3d.com/?page_id=2638). In the years 2021–2022, 4 consecutive Scientific Expedition of the Lublin University of Technology to Central Asia was organised (August 15–28, 2021 – Tashkent: October 10–22, 2021 – Urgench: May 5–18, 2022 – Samarkand: June 5–12, 2022 – Bukhara), which allowed for the digitisation of cultural heritage objects in Tashkent, Chirchik, Urgench, Khiva, Samakranda, Shahrisabz and Bukhara. A total of 13 different employees of the LUT Department of Computer Sciences took part in these expeditions. Thanks to our partners from the Silk Road: Dilbar Mukhamedova from the National University of Uzbekistan, Rahim Kayumov from Samarkand State University, Bakhodir Eschanov from Chirchik State Pedagogical Institute of Tashkent Region, Utkir Abdullaev from Urgench State University and their personal contacts, as well as friends of directors of many museums We were provided with special access to historic buildings in Uzbekistan, which allowed us to perform appropriate 3D scans.

Documenting the condition (the geometry and appearance) of the monuments making up the material cultural heritage of the Silk Road, in view of their number, dispersion and diversity, is a complex process. Working in the field in local conditions is difficult and requires from participants good health, persistence in action and creativity in solving emerging problems. Scanning outdoors for many hours at temperatures up to 42° C in the shade, when specialised equipment, after heating to

a temperature of 60° C, refuses to cooperate, when an overheated tablet slows down the download of data sent by the scanner, shows that your equipment was not designed for such conditions. A competent team, however, was able to overcome all these adversities and imperfection of the equipment. During these expeditions, 110 small and large cultural heritage objects were scanned, bringing in about 400 GB of raw data in the form of point clouds, photos and videos.

During this time, further joint scientific papers were published. The aftermath of the jointly organised International Conference “IT in Cultural Heritage of the Silk Road (IT–CHSR’2021)”, which took place on December 13-15, 2021, was the publication of two more monographs in 2022: *Cultural Heritage of Uzbekistan – from Petroglyphs to the Present Days* and *Computer technologies in sharing the cultural heritage and education of the Silk Road from Uzbekistan*.

The research subject area, developed since 2015, has finally led to the creation of an informal scientific and research school with an international reach in the field of 3D digitisation of cultural heritage objects, their archiving, reconstruction and sharing. Over the years, the authors have carried out comprehensive research in the field of the use of 3D computer graphics technologies in the protection of cultural heritage objects, leading to the perpetual archiving of the appearance and geometric dimensions of these objects and their wide availability. As a result of the activities carried out, the following were developed: many effective methodologies for conducting 3D scanning in in situ conditions, methods of processing the obtained data in the organised Lab 3D laboratory, methods of digital reconstruction of damaged objects, methods of preparing digital models for 3D printing, methods of introducing digital models into the world of virtual reality (VR), methods of disseminating interactive 3D digital models with descriptions in free internet access, and methods of preserving geometry and the appearance of cultural heritage artefacts in digital form.

The content of the monograph includes five substantive chapters and a list of all scientific works by the authors in the field of broadly understood 3D digitisation and 3D modelling. The first chapter is devoted to the issues of threats to which the existing cultural heritage objects are exposed, describing detailed cases from various countries and continents, as well as the methods of their protection. The second chapter presents the knowledge of 3D digitisation techniques, describing more broadly the technologies of terrestrial laser scanning, scanning with the use of structured light and the Structure from Motion technology. The third chapter describes the needs of scanning cultural heritage objects and the selection of 3D scanning devices during organised expeditions, as well as the software used to process the acquired point clouds. Chapter four presents various methodologies for scanning cultural heritage objects and processing the results. The fifth chapter is devoted to the practical implementation of various 3D graphics technologies in relation to objects of tangible cultural heritage in Uzbekistan. Section 5.1 presents research on the inclination of the inner dome of the Golden Mosque in the Tillya-Kori Madrasah in Samarkand, and section 5.2 presents the development of a digital model of the interior of the Juma Mosque in Khiva. Section 5.3 deals with a digital reconstruction of the 12th century

jug from the ancient city of Afrasiab. The scanning and processing of rock petroglyphs still found in the Chatkal Mountains near the city of Chirchik can be seen in section 5.4. Section 5.5 describes the creation of a digital collection of tubiteykas (local headwears) made during a virtual expedition organised during the COVID-19 pandemic. The colour analysis of the tiles forming the mosaic on the front wall of the Sher-Dor Madrasah Aiwan in Registan is presented in Section 5.6. The methodology of generating a virtual exhibition in Virtual Reality technology is presented in subsection 5.7. Finally, subsection 5.8 describes the scanning and manipulation of data on the outfit of the last emir of Bukhara, consisting of a cloak, turban and footwear. Chapter six contains a list of scientific works by the authors (including articles in journals, conference articles, chapters in monographs and editions of monographs) in the field of broadly understood 3D digitisation and 3D modelling of tangible cultural heritage objects, also including activities outside the Silk Road area.

1. Digitisation of cultural heritage

1.1. Threats to cultural heritage

Notre-Dame Cathedral in Paris, France

On April 15–16, 2019, a large fire consumed the 12th century roof and the upper parts of the Notre-Dame cathedral in Paris (Fig. 1.1). The nineteenth-century turret (bell) crowning the roof also collapsed. This happened despite the fire alarm (which, incidentally, signalled the threat twice) and the immediate action of nearly 400 firefighters. Fortunately, most of the cathedral's furnishings was evacuated [1].

A decision was made to rebuild the cathedral. Fortunately, in 2015, historian Andrew Tallon scanned the cathedral from inside and outside [2]. With more than a billion measurement points, the precise 3D model serves as the template for the reconstruction of the cathedral. Andrew Tallon died in 2018, but his work remains.



Fig. 1.1. Fire of the Cathedral of Notre-Dame in Paris [1]

Old Bridge in Mostar, Bosnia and Herzegovina

The Old Bridge in Mostar is a stone bridge over the Neretva River in the city of Mostar – now Bosnia and Herzegovina. It was built in the years 1557–1565 [3] (Fig. 1.2).



Fig. 1.2. The present appearance of the rebuilt Old Bridge in Mostar [3]

The Old Bridge was a symbol of reconciliation between the East and the West, as it connected the Christian and Islamic districts. On November 9, 1993, the Croatian army destroyed the Old Bridge with tank shots during the Bosnian War. The bridge was rebuilt in 1995–2004 using old methods. Photos and archives were used. In 2005, the Old Bridge was inscribed on the UNESCO World Heritage List [3].

Bela Temple in Palmyra, Syria

Palmyra is an ancient Greco-Roman city in Syria, inscribed on the UNESCO World Heritage List in 1980. One of the many monuments of Palmyra was the Temple of Bela (Fig. 1.3). Its creation dates back to 32 BC [4].

On August 30, 2015, militants of the Islamic State in Syria blew up the Bela Temple with explosives (Fig. 1.4). Reconstruction of this monument, as well as many others similarly damaged in Palmyra, is not yet possible.



Fig. 1.3. The Bela Temple in Palmyra in 2008 [4]



Fig. 1.4. Remains of the Bela Temple after its destruction by the Islamic State in 2015 [4]

The international community has attempted to digitally reconstruct Palmyra's monuments from archaeological data and resources. The first such action was the project "New Project Palmyra" [5] initiated by the Palestinian Bassel Khartabil – an open-source developer. It was he who started to recreate the monuments of Palmyra on the basis of photos. Unfortunately, the project was closed in 2012 and the results of the work were lost [5]. Bassel Khartabil himself was killed in 2015 by Syrian soldiers.

The idea of digitally recreating Palmyra's heritage is continued by the #NEWPALMYRA [6] project. This project implements digital 3D models using photogrammetry, collecting photos and videos from tourists from around the world [6]. A large part of the destroyed objects already have their digital reconstructions (Fig. 1.5). In the longer term, based on thousands of photos, it will be possible to recreate the monuments of Palmyra in the digital space.

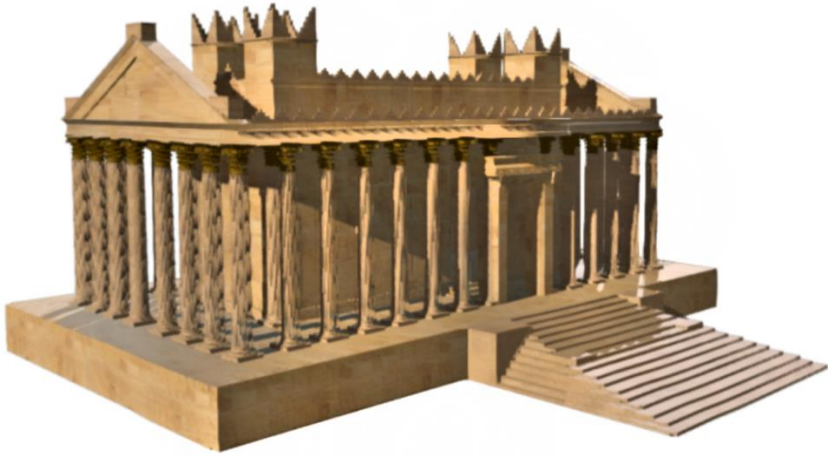


Fig. 1.5. 3D model of the Temple of Bela in the #NEWPALMYRA project [6]

Buddha statues in Bamian, Afghanistan

In the rocks of Afghanistan’s Bamian Province, in the valley of the river of the same name, Buddhist monks carved enormous Buddha statues with internal corridors and windows in the 6th century AC. Five statues were built. The largest one was 55 m high (Fig. 1.6).

It was, because it was destroyed in 2001 [7]. For 25 days, the Taliban fired cannons at statues and finally used explosives to blow them up. This was the result of a decree by the Taliban leader ordering the elimination of all non-Islamic statues and sanctuaries in Afghanistan [7].

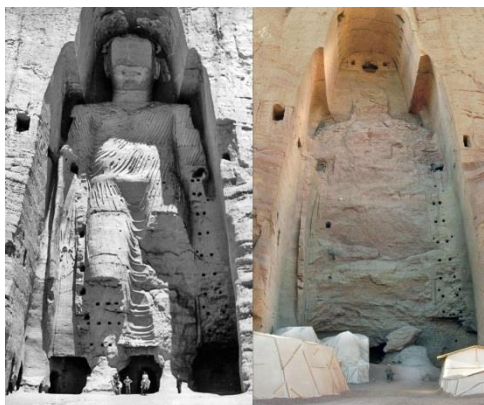


Fig. 1.6. The largest of the Bamian Buddha statues before and after their destruction [7]

In 2003, architectural monuments in the Bamian River Valley were inscribed on the UNESCO World Heritage List. The restoration of the statues could not be done due to the enormous damage and the destruction of the rock material by the local population. On the other hand, attempts are made to recreate the appearance of the statues by means of 3D light projection (Fig. 1.7). Such actions were successively repeated. Will they still be? Probably not in the current situation in Afghanistan.

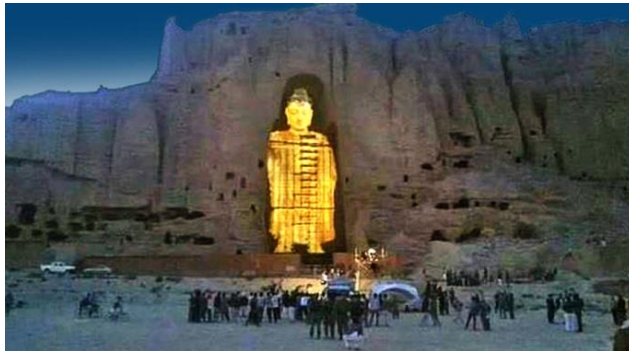


Fig. 1.7. 3D light projection of the Buddha statue in Bamian [8]

National Museum of Rio de Janeiro, Brazil

The National Museum of Rio de Janeiro was opened in 1818 by the Portuguese King Joao VI. It was located in the former royal palace. For over 200 years, it has housed exhibits related to archeology, ethnography, botany, zoology, anthropology and history [9].

On September 3, 2018, the building of the National Museum burned to the ground. 90% of the collection, consisting of over 20 million exhibits, was irretrievably lost in the fire [9].



Fig. 1.8. Rio de Janeiro National Museum Burning [9]

Petroglyphs from South-Western Arizona

Petroglyphs, or rock drawings, are very often one of the oldest objects of cultural heritage. Formed hundreds of thousands of years ago, they are witnesses of the emerging human species.

It seems that large boulders with drawings carved on them should be durable and indestructible. Unfortunately, even they are subject to theft, vandalism or destruction, for various purposes: from obtaining raw material to acquiring land (Fig. 1.9). Such cases are reported from all continents.

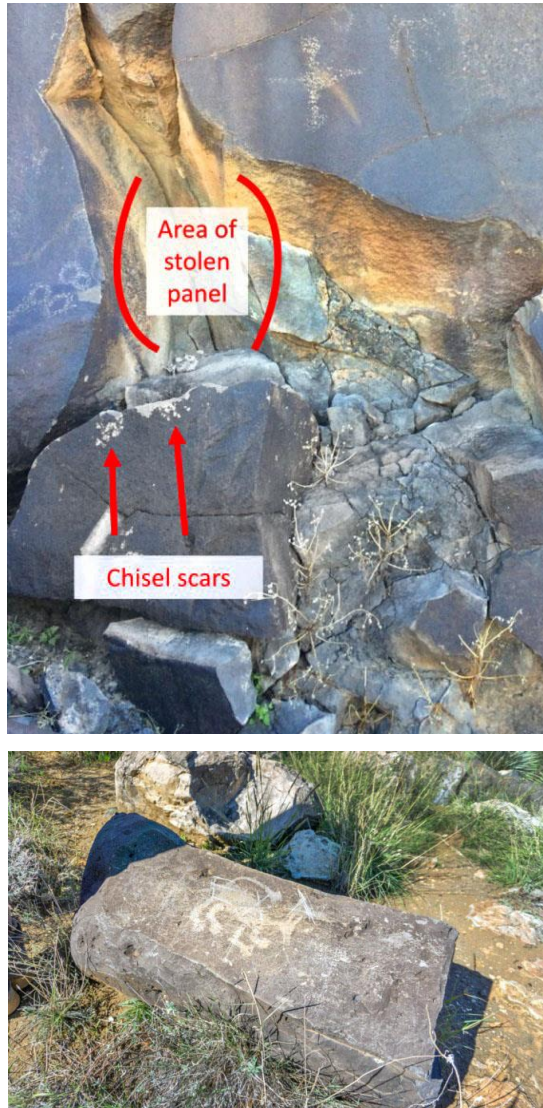


Fig. 1.9. Stolen and orchestrated petroglyphs [10]

Durbar Square in Patan, Nepal

Patan Durbar Square is one of the three Durbar Squares in the Kathmandu Valley inscribed on the UNESCO World Heritage Site List. The square is famous for its 17th century Buddhist and Hindu temples [10].

On April 25, 2015, Nepal was hit by a strong earthquake (7.9 on the Richter scale) that destroyed many historic buildings, including the temples at Patan Durbar Square (Fig. 1.10).

a)



b)



Fig. 1.10. Temple at Patan Durbar Square: (a) before, (b) after the earthquake [10]

Azure Window on Gozo, Malta

The 28-meter-high natural stone arch was located on the island of Gozo off the coast of Malta (Fig. 1.11). It was one of the flagships of Malta.

On March 8, 2017, after a period of strong storms, the Azure Window collapsed. It will rather not be rebuilt. However, thanks to digital technologies, it can be viewed on the screen or by using virtual and augmented reality (Fig. 1.12).



Fig. 1.11. Azure Window – a view from 2009 [11]

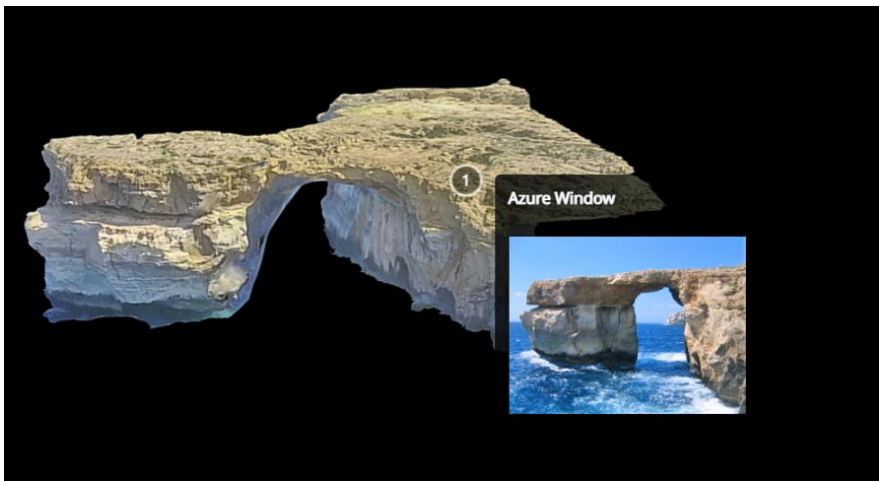


Fig. 1.12. 3D Azure Window model for applications in virtual and augmented reality [12]

1.2. Protection of world cultural and natural heritage

The examples in Chapter 1.1 show the multi-vector threats to cultural and natural heritage. Some of the threats are random, but some, unfortunately, result from deliberate human activities.

Among other goals also to protect monuments, in 1946 the United Nations (UN) established the United Nations Educational, Scientific and Cultural Organisation (UNESCO) [13]. Over 190 countries have become UNESCO members and 12 are associate members [13].

In 1975, the Convention Concerning the Protection of the World Cultural and Natural Heritage entered into force. The convention obliges the signatory states to identify, protect, conserve, restore and pass on to future generations their cultural and natural heritage. It establishes the protection of cultural and natural heritage of exceptional universal value, including by granting international protection status and by inscribing it on the UNESCO World Heritage List.

Cultural heritage is related to human activity, as opposed to natural activity. Cultural heritage is divided into tangible and intangible.

The concept of tangible cultural heritage is obvious. On the other hand, the intangible heritage consists of [14]:

- oral traditions and expressions (e.g. language, storytelling),
- performing arts (e.g. singing, dancing, theatre, feasting),
- social practices, rituals and festive events,
- knowledge and practices concerning nature and the universe,
- knowledge and skills to produce traditional crafts.

Protection concerns the following areas [14]:

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

Documentation is related to the acquisition and storage of various types of information about cultural heritage objects.

Protection is activities against damage, destruction or other loss of heritage objects.

Reconstruction is the process of visualising cultural heritage objects in order to better understand them.

Renovation is a set of activities including: integration and replacement of non-original elements, their reconstruction, retouching and supplementation.

Conservation is activities that extend the life of cultural heritage while enhancing the message of its essential story and values.

Dissemination concerns the representation and visualisation of heritage objects with the use of various technologies – from traditional (e.g. drawing, photo) to modern – digital (internet portals, virtual and augmented reality environments).

Popularisation (dissemination) aims to reach the widest possible audience in order to familiarise them with the cultural heritage.

Digital technologies may be used in a significant part of the above-mentioned protective measures. This particularly applies to activities related to documenting the dimensions and appearance of heritage objects (creating the so-called perpetual archives) and their dissemination and dissemination.

With the use of modern devices and software, documentation processes can be carried out faster, more accurately and cheaply than with any traditional methods. This is especially true for measurements (size, geographic location, etc.) and the appearance of objects (mainly colour).

Modern information technologies in the present times of the development of Internet data transmission networks and universal access to computers (including technologically advanced mobile devices) create an unimaginable field for the dissemination and spread of information (including appearance) about cultural and natural heritage. Through the Internet, mass audiences can be reached all over the world.

Information technologies can also be used to assist in protection (e.g. digital surveillance system), reconstruction (e.g. digital reproduction of the appearance of damaged objects), renovation (e.g. 3D printing of missing elements of cultural heritage objects) and conservation of objects (e.g. examining the condition of objects and searching for problems, changes in the state requiring the intervention of conservators).

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2. Methods, techniques and technologies of 3D scanning

2.1. 3D scanning techniques

There are many solutions for gaining knowledge about the shape and dimensions of three-dimensional objects. These include such methods as:

- Manual dimensioning.
- Dimensioning using computer/robotic contact systems.
- Dimensioning with rangefinders.
- Determining the depth on the basis of shadows and a set of appropriate light sources.
- Laser and LIDAR scanning.
- Structured light scans.
- Long and short range photogrammetry.

It should be added that in the case of objects of material cultural heritage – museum artefacts, architectural objects or sites including archaeological excavations, it is important to automatically obtain, in addition to the shape, information about the colour and texture of the objects. Of the methods mentioned above, only the last three guarantee this. Capturing information about the texture is very important if in the future the digital models created are to be destined for prepared virtual exhibitions, virtual museums or worlds in Virtual Reality technology. With the above in mind, only the last three methods of data acquisition will be discussed in the following sections.

2.2. Laser scanning

Laser scanning, also known as LIDAR (Light Detection and Ranging), is a technology belonging to the group of active photogrammetric systems using coherent laser light. Laser scanning is a group of methods and devices that use a laser beam to determine the distance from an object (it is therefore an extension of the idea of laser rangefinders). A laser beam, most often with a wavelength in the infrared range, is emitted from the scanner device. Unlike a rangefinder, however, this beam is not emitted in one direction towards the device, but changes direction (angle) by sampling/scanning a certain area around the scanner. With this ray, the distance from the scanning device to the point from which the projected ray is reflected is measured. The device captures the reflected beam and calculates the distance using the time method – time of flight or the more precise phase shift method.

Thanks to various types of scanners, we obtain a very wide range of applications. Generally, we can distinguish several basic groups of laser scanners:

- Short-range scanners (handheld and stationary).
- Long range scanners (stationary and mobile).
- Very long range scanners (aerial and satellite).

The first group includes small stationary or handheld devices that measure at short distances (0.2–2 m). Stationary scanners most often use laser displacement in one axis and rotation of the scanned object to create a map of its surface. The limitation of their use is usually the small space of the chamber in which the object is placed and in many cases the necessity to fix the artefact mechanically, which in many situations is impossible in relation to museum objects (Fig. 2.1). But is not a problem with regard to complete objects. The device parameters are presented in Table 2.1.

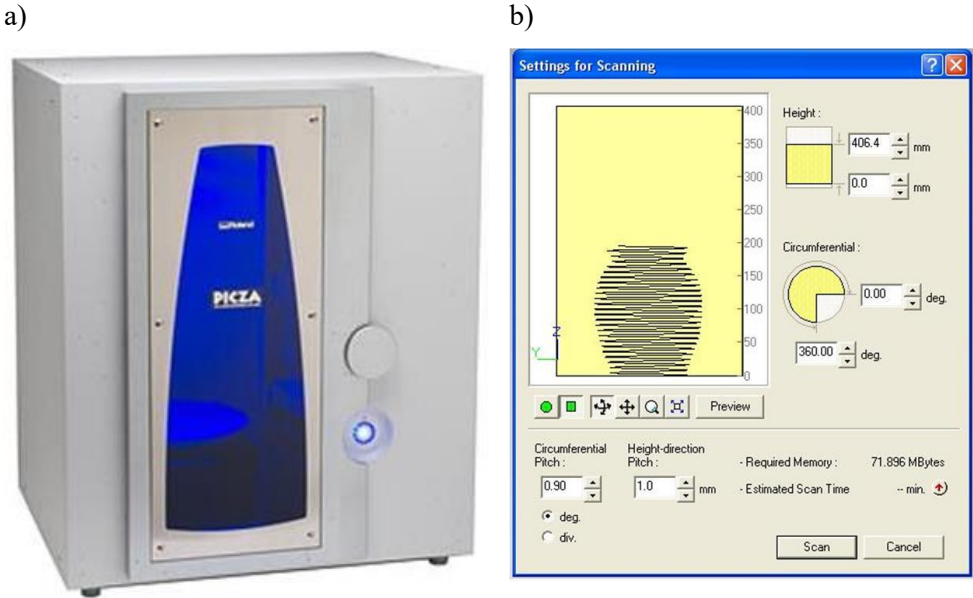


Fig. 2.1. (a) Roland PICZA 3D Laser Scanner LPX-600 [1], (b) preview of the jug scanning process [2]

Handheld scanners perform a quick sweep of the space in front of them to obtain a map of the surface, which is then matched to the next map made after the scanner has been moved. Most often, adjustments are made on the basis of markers applied to the object’s surface or its surroundings. Sticking markers to historic objects is in most cases unacceptable, which means that this method of 3D scanning is not currently used in the acquisition of the surface of museum artefacts (Fig. 2.2). Basic parameters of this device are presented in Table 2.2. There are many different technical solutions of scanners working in this technology, for example Creaform MetraSCAN 3D or HandySCAN 700 [3].

Table 2.1. Scanner Roland PICZA 3D Laser Scanner LPX-600 detailed description [2]

Name	Description
Table size	Diameter 254 mm (10 in.)
Maximum scanning area	Plane scanning: Width 254 mm (10 in.), height 406,4 mm (16 in.) Rotary scanning: Diameter 254 mm (10 in.), height 406.4mm (16 in.)
Scanning pitch	Plane scanning: width direction 0.2 to 254 mm, height direction 0.2 to 406.4 mm. Rotary scanning: circumference 0.18 to 3.6 degrees, height direction 0.2 to 406.4 mm
Repeat accuracy	±0.05 mm (This figure reflects standard scanning conditions established by Roland DG)
Maximum table load weight	5 kg (11 lbs)
Laser	Wavelength: 645 to 660 nm Maximum output: less than 0.39 μ W (maximum output of the laser light emitted inside housing is 0.1 mW)
Sensor	Non-contact laser sensor
Scanning method	Spot-beam triangulation
Operating speed	Table rotation speed: 9 rpm, head rotation speed: 4.48 rpm, Maximum head movement speed: 37 mm/sec.
Interface	USB (compliant with Universal Serial Bus Specification Revision 1.1)

a)



b)



Fig. 2.2. The ZScanner ® 700: (a) general view [4], (b) the scanning process of jug [2]

Table 2.2. Details of the ZScanner ® 700 [2]

Name	Description
Weight	1.3 kg
Dimensions	172 x 260 x 216 mm
Speed	18,000 measurements/s
Laser class	II (safe for the eyes)
Cameras	3
Accuracy XY	50 µm
Resolution	0.1 mm in axis Z
Texture resolution	50 to 250 dpi
Depth of measurement	30 cm
Exported formats	<i>.DAE, .FBX, .MA, .OBJ, .PLY, .STL, .TXT, .WRL, .X3D, .X3DZ, .ZPR</i>
Certificate	CE
Data transfer	FireWire

The second group includes devices that use a laser beam to carry out measurements at distances from about 60 cm to several kilometers.

This group can be divided into subgroups:

- Stationary scanners – TLS (Terrain Laser Scanning).
- Mobile scanners based on GNSS (Global Navigation Satellite Systems).
- IMMS mobile scanners based on SLAM (Simultaneous Localisation and Mapping).

Regardless of the group to which the laser scanner belongs, the basic principle of scanning is similar. The laser beam changes the angle to the scanner head in 1 axis. This is similar to a barcode scanner. So a certain line of points in space from which the scanner beam is reflected is registered. These points are located in the area of the circle defined by the range of the scanning device, in other words, within the radius of this circle. Objects in the area of the circle reflect the scanner beam and read the distance. The distance (along the radius) and the current radius angle on the circle determines the position of the point on the plane of the circle. The circle plane coordinates allow to locate this point in 3D space.

Only those surface points of the object along the path of the ray where the ray first reached are recorded. Points located further (e.g. on the next wall) are obscured and it is not possible to scan them during the current scan.

In the case of TLS scanners, in order to be able to obtain greater coverage of the scanning area than a single circle, the rotation of the scanning device is performed in the axis which is the diameter of the scanning circle. During the rotation of the scanner placed on a tripod, a series of scans in a circle is carried out, which in effect covers the space in a certain sphere around the position of the scanner. Still, the scanner cannot scan surfaces obscured by others.

To be able to scan all surfaces of the object, it is necessary to perform a series of scans in different positions of the scanner in relation to the object. Single scans after

gluing in the post-processing process lead to a complete digital model of the scanned object. An example of a device working in TLS technology is the Leica HDS 3000 scanner [5]. In their field work, the authors used the FARO Focus scanner – X 330 and S 350+ models (Fig. 2.3), which is characterized by the parameters given in Table 2.3.



Fig. 2.3. Horizontal and vertical rotation of the laser scanner [6]

Table 2.3. Basic parameters of the FARO Focus S 350+

Parameters	Faro Focus S 350+
Range	Spherical range with a radius of 350 m, measurement both inside and outside buildings, possibility of scanning in difficult lighting conditions, dusty conditions.
Distance measurement systematic error (accuracy)	±1 mm
Points gathering speed	up to 2 million points per second
Photo module	HDR function, up to 165 megapixels in colour
Mobility	weight 4.2 kg
Dimensions	230 x 183 x 103 mm
Working temperature	-5 up to 40°C
Data storage	SD, SDHC™, SDXC™ cards
Working time	up to 4.5 hours
Scanner positioning	GPS and GLONASS. FARO Focus scanners are also designed to be operated with a drone
Tightness	IP54 (industry standard)

It should be emphasised that the FARO Focus scanner has a photo module that takes a series of photos together with the recording of coordinates, which enable them to be automatically mapped to the obtained 3D surfaces. In the presented device, the program decomposes the photo by collecting information about the colour of individual pixels and assigning them to individual points of the 3D model.

In the case of mobile GNSS scanners, the rotation of the scanner has been replaced by the movement of the vehicle carrying the scanner. The position change is determined on the basis of the GNSS global position reading and the status of other sensors such as a compass or an inclinometer.

The third type refers to devices whose movement during scanning can be carried out along any path and the device position is not read from the global location system. Most often, such a situation takes place in interiors and areas with difficult to read the GNSS signal.

Simultaneous Localisation and Mapping (SLAM) scanning is a method of simultaneously creating a digital map of the environment (in the form of a point cloud) and locating a recording device in relation to this map. Subsequent readings of the scanner are therefore added to the database about the environment, after they are matched on the basis of compliance with the existing cloud and the readings of internal sensors such as tilt and direction.

Very long range scanners are based on solutions similar to GNSS. An aircraft travelling in a straight line (drone, plane) carries out a laser scan of the area over which it is flying. By keeping the ceiling, direction and speed constant, the problem of matching successive linear measurements can be simplified. Due to the large distance and the area covered, the resolution and accuracy of such a scan is much lower than in the case of terrestrial methods. On the other hand, the scan of a large area is carried out much faster.

2.3. Structured light scanning

Structured light scanning uses the possibility of determining the spatial shape of an object on the basis of its image from properly calibrated perspective cameras and projection of a flat image with a certain structure onto this object.

The scanning uses a small number of cameras (1–3) precisely calibrated and aligned with each other. Thanks to this, it is possible to obtain high precision of positioning points on the surface of the scanned object (in the scope of the scanning distance at which the cameras are set). Thanks to the knowledge of the parameters of the scanner cameras, it is possible to determine the actual size of the scanned object.

A flat shape projected onto an object (most often by means of an LCD projector) is called structural light due to a certain uniform structure of such an image (fringes, grids, etc.). Determining the shape of the scanned surface is carried out by combining the search for characteristic points and their equivalents in the images and projection on the object of a flat structure.

Comparing the shape of the pattern displayed on the object with its original appearance allows the appropriate algorithms to determine the size, shape and location of parts of the object's surface.

Performing a single scan creates a 3D surface point cloud of an object similar to the points obtained from laser scanning. However, already at the stage of a single scan, these points are pre-combined into surface meshes and the textures read from the scanner cameras are assigned to them. Due to the necessity to project an appropriate image onto the surface of the scanned objects, this type of scanners scan surfaces at distances up to several meters from the scanner.

There are two subgroups in the group of structured light scanners:

- stationary scanners,
- handheld scanners.

The scanners from the first subgroup are most often stand-alone solutions – they require a permanent place where the scanner can scan after calibration without being moved. The advantage of a fixed scanner setup is the ability to project multiple patterns in succession onto a single object setup, which improves scanning accuracy. Often, together with the scanner, a (automatically controlled) rotary table is used, a place for the scanned object. In this way, the process of scanning the entire surface of the object was automated and at the same time it was easier to adjust individual scans (the axis and angle of rotation of the next scan in relation to the previous one is known).

Scanning with a stationary scanner, even using a table, may not cover the entire surface of an irregularly shaped object. Scanning the entire surface of the object would require multiple scanning sessions with different arrangement of the object on the table. An example of the use of the device used by the authors is shown in Fig. 2.4.

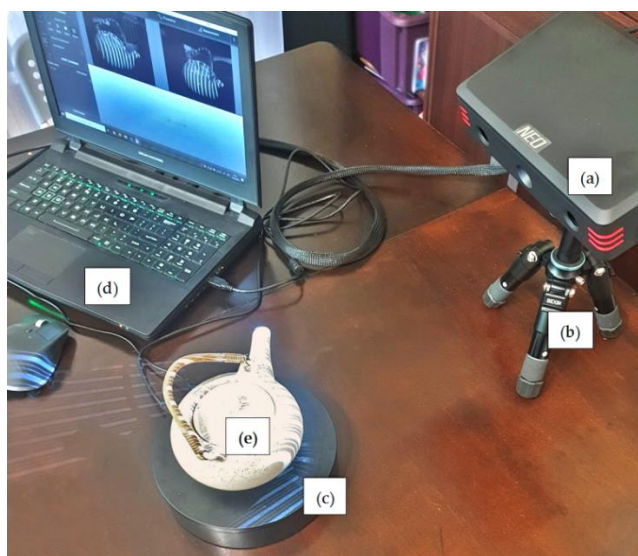


Fig. 2.4. 3D digitization of an object with a RangeVision NEO scanner: (a) scanner, (b) tripod, (c) rotating table, (d) laptop with software, (e) scanned object. By the authors [7]

An idea to solve this problem are handheld scanners where a single scan has been reduced to such a short time (fractions of a second) that it can be performed even if the scanner is not in a stable position but is held in the hand. The individual scans can be performed so quickly that they can be treated as a series as the scanner is moved along the surface of the object. This results in hundreds of partial scans of one object, covering its entire surface.

To make it easier to match such a large number of scans later, they are pre-matched “on the fly” during the scan to form pre-matched groups. Scanning of an object can be carried out in batches (e.g. due to the need to relocate the object), so there can be several groups for one object.

Matching groups is done with the support of an operator who can determine the coarse relative position of the groups so that the matching algorithm has a sufficiently narrowed search area. As a rule, it is enough for the operator to indicate several (at least 3) corresponding points to arrange the groups in an adjusted manner.



Fig. 2.5. Construction of Artec Spider scanners [11]

After the groups are combined, the individual partial scans are finally fitted and the coordinates of each scan are recalculated to one coordinate system. This procedure is called global registration and must be performed before the cloud is exported or the mesh model is generated. Today, there are many devices on the market that work in this technology, which were used for data acquisition of various cultural heritage objects: HDI Advance R3X, LMI TECHNOLOGIES, Canada Konica Minolta Vivid-900 GOM, ATOS Standard [8], Konica Minolta Vivid-910 [9], Kinect Fusion [10].

Scanners of this type also have the ability to capture information about colour and texture. These data are not collected with the same frequency as the surface area, so when performing post-processing, care should be taken not to remove the so-called colour frames that contain the data. Figures 2.5 and 2.6 show the Artec Spider and Artec Eva scanners used by the authors, and Table 2.4 shows their main operational parameters.



Fig 2.6. Construction of the Artec Eva scanner [12]

Table 2.4. Comparison of the basic parameters of scanners [11, 12]

Parameters	Artec Eva	Artec Spider
Texture capture capability	Yes	Yes
Scanning technology	Structured white light	Flashing light bulb, blue light (no laser)
3D resolution, max.	0.5 mm	0.1 mm
3D point accuracy, up to	0.1 mm	0.05 mm
Linear field of view, Height x Width	214 x 148 mm up 536 x 371 mm	90 x 70 mm up 180 x 140 mm
Scanner distance from object	0.4–1 m	0.17–0.35 m
Video frames, up to	16 fps	7.5 fps
Record output formats	OBJ, PLY, WRL, STL, AOP, ASCII, PTX, E57, XYZRGB	OBJ, PLY, WRL, STL, AOP, ASCII, PTX, E57, XYZRGB
Weight	0.85 kg	0.85 kg
Interface	1 x USB 2.0 or USB 3.0	1 x USB 2.0 or USB 3.0
Supported systems Windows	Windows 7, 8, 10 – x64	Windows 7, 8, 10 – x64
Minimum computer requirements	I5 (recommended I7), 8–12 GB RAM, NVIDIA GeForce 2GB	I5 (recommended I7), 8–12 GB RAM, NVIDIA GeForce 2GB

2.4. Photogrammetry

It is a technology in which complex laser systems or calibrated sets of cameras and projectors have been replaced by using only the image from perspective cameras, the parameters of which are known only to a certain extent (as a rule, the relative position of the cameras towards the object is unknown). Thus, photogrammetry is the technology of obtaining reliable information about three-dimensional objects (their shape) through the process of registration, measurement and interpretation of photographic images.

Photogrammetry can be divided into two groups according to the scanning range:

- long-range photogrammetry,
- close-range photogrammetry.

Long-range photogrammetry is carried out similarly to laser scanning from aircraft, however, instead of laser measurement, a series of photos is taken with a camera directed at the earth's surface – aerial or satellite photos.

Short-range photogrammetry refers to objects that are within the range of an “average camera” used by an operator on the ground. This can mean both an object in the immediate vicinity and a building far away, the unwritten limit of close photogrammetry is 1,000 feet (i.e. about 300 m).

The lack of use of calibrated cameras and a series of integrated sensors is compensated by the number of photos analysed (which can be counted in thousands for one object).

Photogrammetric analysis is carried out in several stages to obtain a 3D model of the scanned object. During these stages, the following information is reproduced:

- mutual position of the cameras,
- camera parameters (if not known),
- coordinates of characteristic points and their counterparts in individual images,
- 3D coordinates of characteristic points (relative to the position of other points, on an arbitrary scale).

Photogrammetry does not allow direct determination of the real size of objects. From the images alone, it is not possible to determine the actual distances between the characteristic points (point cloud scale). This information is obtained by placing reference objects (scales) in the photographed area or by sticking markers at known distances between them. At present, due to the widespread use of methods and applications based on photogrammetry, calibrated digital cameras from leading manufacturers are available, allowing to obtain a metric scale (<https://en.elcovision.com/messkameras.html>).

In general, photogrammetry comes down to taking a series of photos of the object we are interested in so that subsequent photos “overlap” (i.e. partially cover the area visible in the previous photo – the required coverage of photos according to the literature data should reach up to 80%), and their brightness and the focal length was relatively unchanged. Photographs of the subject should be taken from various positions to show all sides and details of the subject to be photographed. Photogrammetry is suitable for both small museums and large architectural objects.

In the case of small museum exhibits, it is possible to place them on a turntable, which is gradually rotated, and the camera is placed on a tripod. You should remember to crop photos “tightly” so that the background of the object, which is treated as noise, does not have a significant impact on the quality of the obtained digital 3D model. In the case the object is bigger, we have to circle around the object with the camera. Such action in the case of architectural monuments leads to some difficulties in framing the object (there is not always enough space to maintain the same focal length). In addition, when we stay at the facility for a short time, there is always a situation that some photos will be taken against the sun (unless the day is cloudy). In practice, from 60 to 200 photos of the object should be taken (their number depends on the size of the object and the ability to approach the object).

The Structure from Motion (SfM) technique used in photogrammetry is used to generate three-dimensional structures based on two-dimensional image sequences that meet the above requirements. 3D models obtained using the SfM method do not always look good enough, but it is possible to smooth them using various software for editing mesh 3D models, such as the free Blender program (Fig. 2.7).

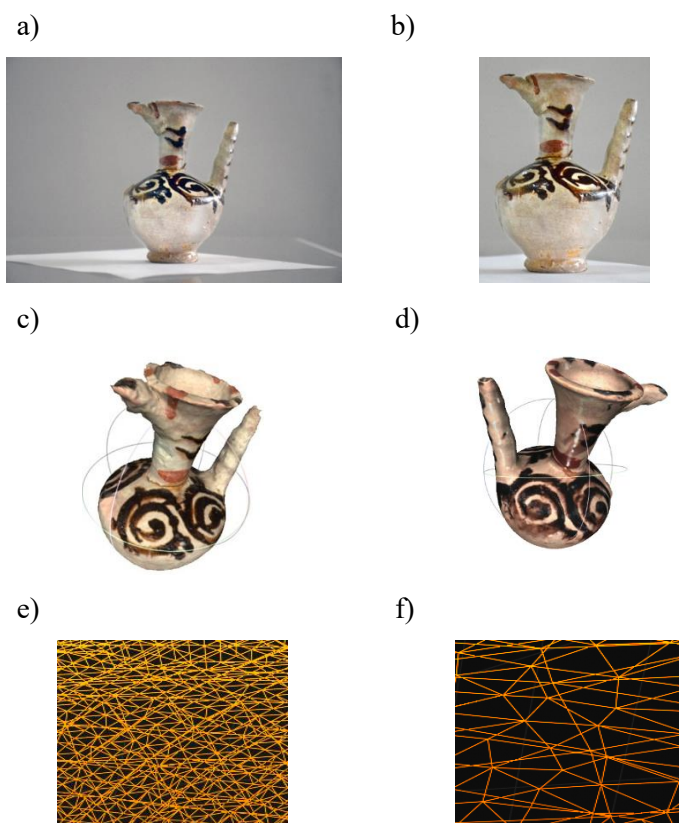


Fig. 2.7. Jug: (a) primary photo, (b) photo after cropping, (c) digital 3D model generated using SfM technology, (d) 3D model after additional processing, (e) mesh of the original model, (f) mesh after reduction. By the authors [13]

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3. 3D data acquisition tools

3.1. 3D scanning needs and selected methods

In the course of the work preceding the scanning sessions, potential historical sites from the Silk Road cultural heritage area were identified in order to distinguish between the types of historical sites. The listing of these types was carried out in terms of the scanning method that could be used. In the course of the reconnaissance, two main groups of objects were distinguished:

1. Objects with dimensions not exceeding a few meters.
2. Objects with the dimensions of buildings (sizes from several to several dozen meters).

The first group includes mainly exhibits presented in Uzbekistan's museums: ceramic utility objects, stucco elements, dishes, but also tombstones, sculptures and clothing.

The second group includes historical buildings from the times of the Timurids – the rulers of today's Uzbekistan in the heyday of the Silk Road – and later.

While assessing the objects of the first group (Fig. 3.1) in terms of technical aspects of their scanning, the following conclusions were drawn:

- The vast majority of objects are various types of ceramic elements that may be glazed and painted decorations.
- Most items are sized and shaped to allow for easy movement and placement on scanning aids – such as turntables.
- Some items cannot be moved due to their fragility or size.
- The shapes of the items range from flat plates to intricate carvings to multi-material garments with numerous decorations.
- One group of items – clothing, will require scanning in one position due to shape changes when moving.
- Another group of elements – petroglyphs, will require field scanning, and therefore the use of equipment that can work without a permanent power source.
- All these elements (except petroglyphs) are available in closed, well-lit spaces with access to a power source.
- Due to legal conditions, it will not always be possible to scan these objects in a place devoid of the presence of outsiders.



Fig. 3.1. Examples of objects belonging to the first group. By the authors

Similarly, while assessing objects of the second group (Fig. 3.2) in terms of technical aspects of their scanning, the following conclusions were drawn:

- Virtually all objects from this group are open-air structures.
- The scanned buildings are of considerable height and most often have rich, glazed stucco both inside and outside.
- Due to legal conditions, it will not be possible to scan these objects without the presence of outsiders.
- Because of weather conditions, scanning will have to be performed in strong sunlight and high temperatures.
- Due to legal requirements (prohibition of the use of drones), it is not possible to scan objects from the air – it will not be possible to obtain a full scan (containing the part visible from above). Scanning from available places on the ground allows to get a full view of the elevation, i.e. the most historically significant parts of the building.
- During the scan, access to the power sources will be difficult.

a)



b)



c)



Fig. 3.2. Examples of objects from Uzbekistan belonging to the second group: (a) Sher-Dor Madrasah, Registan Ensemble, Samarkand, (b) Shah-i-Zinda Mausoleum, Samarkand, (c) one of the mosques, Bukhara. By the authors

While analysing the conclusions, they were confronted with the available scanning methods presented in Chapter 2.

In the case of the first group, the available solutions turned out to be structural light scanning methods and close photogrammetry. The possibility of using short-range laser scanners has been rejected due to the necessity to record the colour of the surface of the scanned objects.

At a later stage, the potential effects that can be achieved with the indicated methods using the existing equipment were analysed. Photogrammetric methods, although providing high quality of the colour of the object's surface, do not ensure high accuracy of the model and the dimensions of the mapping obtained must be calibrated to reflect the real dimensions of the object. Structural light scanning methods ensure the accuracy of mapping at the level of fractions of a millimeter with simultaneous obtaining an acceptable colour representation of the surface.

The scan execution mode was also important. Photogrammetric methods do not require the use of specialised rotary tables and the time of taking one photo/scan is measured in seconds. The size of the surface is also not very important as long as there is free access to or view of every fragment of it. For structured light scanners, different kits require different approaches. Stationary scanners in the rotary table mode require that the position of the scanner remains unchanged throughout the entire scanning session (execution of a series of scans around the object), while manual scanners can be freely moved during the scanning of a given area of the object. Structured light scanners also usually have a fixed distance to the object's surface and the size of the area scanned in a single shot. In the case of photogrammetric methods, it is much easier to adjust these values to the requirements of the objects.

To sum up, the use of hand-held structured light scanners was considered as a universal solution that meets the requirements, while the optimal solution for objects of small dimensions was the use of a stationary structured light scanner equipped with an automatically controlled rotary table.

One of the problems in both groups was the high probability of the necessity to perform scanning in the presence of tourist traffic. During earlier LUT expeditions to Central Asia, a methodology for dealing with scans of architectural objects was developed and successfully tested [1]. Based on these experiences, an analogous procedure was developed in the case of objects from the first group.

3.2. Devices used

After analysing the conclusions presented in the above chapter, the equipment that will be used during the scanning of objects in the first group and the second group was selected. The project team had the following equipment (Fig. 3.3):

- A. RangeVision NEO structured light stationary scanner with a dedicated rotary table (Fig. 3.3a).
- B. Structured light handheld Artec EVA and Artec Spider scanners, plus a rotary table as well as a battery allowing field scanning (Figs. 3.3b and 3.3d).
- C. Faro Focus X 330 and S 350+ stationary laser scanners (TLS) with dedicated stands and spare batteries (Fig. 3.3c).
- D. Mobile PC computer – MS Surface 7 Pro, with software for cooperation with the above-mentioned scanners (Fig. 3.3a).

a)



b)



c)



d)

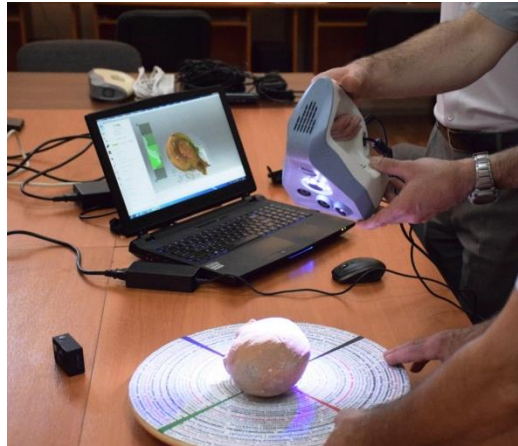


Fig. 3.3. Scanners and stations for 3D scanning: (a) RangeVision NEO, (b) Artec EVA, (c) Faro Focus S 350+, (d) Artec Spider. By the authors

For objects from the first group, due to their diversity, it was decided to use both the stationary scanner A and the handheld scanner B.

Type A scanner

This scanner was used to scan small objects – easy to move and place on an automated turntable. Due to the stationary nature of the scanning and lower hardware requirements, desktop computers provided by partners from Uzbekistan were used to control the operation of this scanner.

Type B scanner

This scanner was found to be appropriate for the scanning of the remaining elements from group one. It was decided to use only the EVA scanner due to greater versatility and sufficient scanning accuracy. The use of this mobile handheld scanner was found to be appropriate, especially in the scanning of 2 distinguished subgroups: clothing and petroglyphs. In the first case, due to the possibility of scanning from any position and a sufficient distance not to move the scanned garment. In the second case, due to the possibility of scanning without connection to the mains. Computer D was also assigned to set B due to its mobility and the possibility of carrying/operating both devices (scanner and computer) simultaneously by one person.

In the case of objects from group 2, it was decided to use the Faro Focus S 350+ scanner from set C. The choice was made due to the possibility of using the colour registration of the scan in the HDR mode. The implementation of the scanning process did not require cooperation with the control computer.

As a result, 3 sets of scanning instruments were created and used during the project implementation:

- **Set 1** includes a scanning module on a tripod, an automatic rotary table, calibration panels and a control computer. A single scanning session consists of the implementation of 12 partial scans of an object automatically rotated on a turntable. The duration of a single scan session is about 90 seconds. Depending on the shape of the object, 1 to 5 sessions are required to fully scan it. Due to the specificity of scanning in this mode, the object cannot be significantly larger than the diameter of the rotary table. Due to the positioning of the object always in the same position in relation to the scanning head, maintaining the uniformity of the brightness of the surface texture of the object is relatively easy.
- **Set 2** consists of a scanning module held in the hand of the operator and a computer controlling the scanning process. Optionally, the set includes a portable battery that allows one to scan anywhere. Scanning takes place by moving the scanner towards the surface of the object so that all parts of its surface are successively illuminated by the scanner. The scanning head performs from a few to a dozen or so partial scans of the surface per second. With relatively slow movement of the scanner, successive scans contain enough corresponding areas to fit together. The role of the computer is to initially combine these scans on the fly during the scan so that the operator can see what area of the object is already scanned. The duration of one scanning session is not rigidly defined and depends on many factors. It may take several sessions to fully scan an object.
- **Set 3** consists of a self-working scanning head placed on a tripod. The head makes 2 to 3 revolutions during one scan. The role of the tripod is to provide a stable support so that the head is not exposed to vibrations or displacements. The area around the scanner is scanned, all points that can be reached by the laser beam from the scanner at a distance of up to 350 m from the scanner are recorded. The scanner also takes photos which are used to apply colour to the scanned points. The single scan procedure takes from several minutes to 1.5 hours, depending on the settings.

Scanning the entire object requires a series of scans from positions ensuring that the scanner beam reaches all relevant surfaces of the object. Having a replacement battery allows the scanning process to be carried out without long breaks. The scanner can be controlled remotely from a web browser or native software, but the participation of the computer in the scanning process is not necessary and maintaining a Wi-Fi connection reduces the device's working time on a single charge.

3.3. Software used

Each of the 3 sets used is based on a different type of scanner. Each of them has dedicated software that controls and processes raw data collected by the scanner. The specificity of these data also means that the end results are not always of the same type. In the case of set 1, the controlling software and data processing tool is RangeVision ScanCenter (Fig. 3.4).

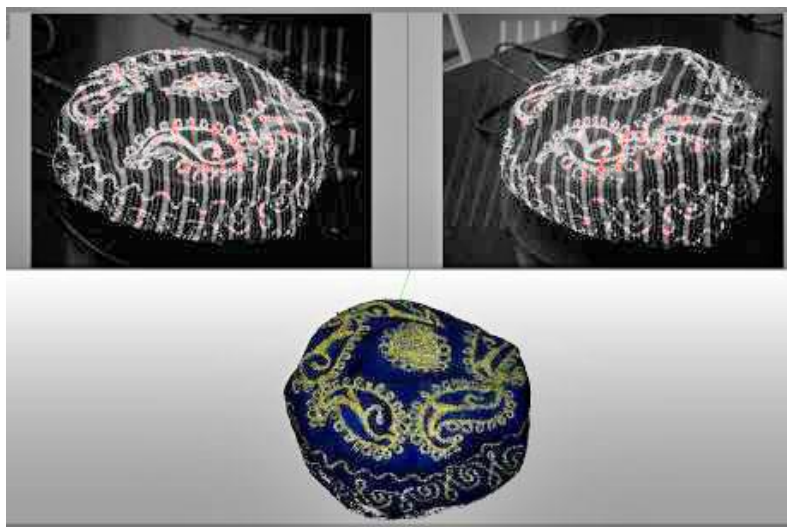


Fig. 3.4. RangeVision ScanCenter window while scanning is in progress. By the authors

The primary task of the software is to control the scanning process. The software allows to carry out the calibration process, select image parameters and support the correct positioning of the object, and finally preview the course and effects of the scan. Depending on the mode, scanning is carried out automatically with the participation of a rotary table or with manual movement of the object or scanner between successive partial scans.

The second task of the software is to process raw data from the scanning process into a 3D model with acceptable parameters. The process includes: removing unwanted elements from partial scans, matching partial scans or their groups to each other, performing global registration to bring all data to one coordinate system (Fig. 3.5).

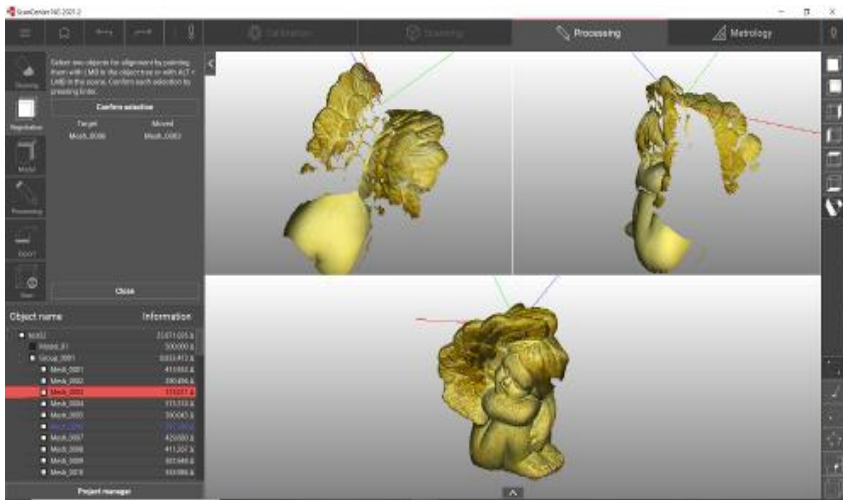


Fig. 3.5. RangeVision ScanCentre window while adjusting scans. By the authors

The effect of these steps is to obtain a dense cloud of points forming the surface of the scanned object. In the process of triangularisation, it is transformed into a 3D mesh with a given density (number of triangles). The texturing process allows to apply colour to the mesh based on the photos taken during the scanning process.

The software for set 2 – Artec Studio (Fig. 3.6) in general is similar to the one described above. The basic differences, apart from the interface, result from the specificity of scanning with a manual scanner – the number of partial scans is many times greater. It can reach several hundred or even several thousand so-called frames. These sub-scans are already pre-adjusted within one scanning session, however, the quality of this adjustment may not be satisfactory.

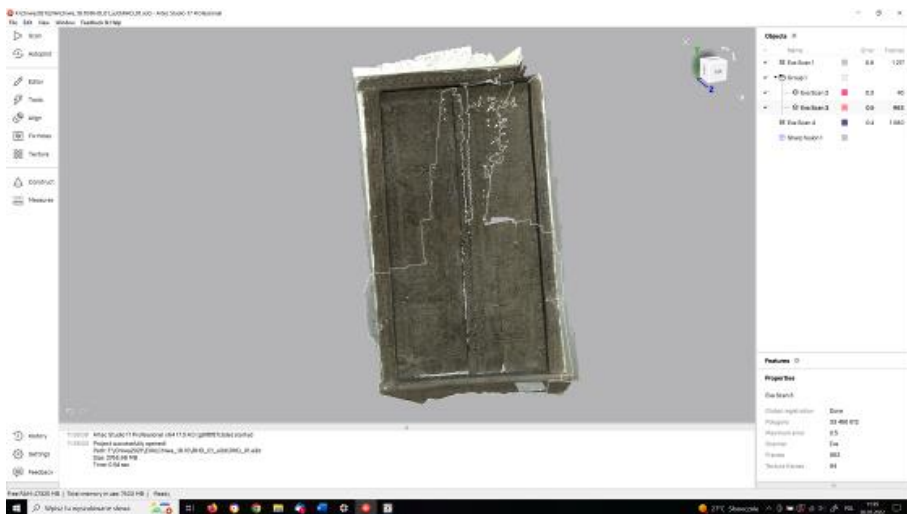


Fig. 3.6. ArtecStudio window while matching scans. By the authors

Scans are processed most often in groups corresponding to subsequent scanning sessions. In this way, removing unwanted elements or matching subsequent scanning sessions takes place on the entire group at once.

The other steps are analogous: global registration of the entire set of scans, generation of a triangle mesh, creating a texture based on photos.

In the case of both of these sets, colourisation – the creation of textures is carried out directly on the basis of photos that are part of the data from the scanning process. This ensures a fairly accurate reproduction of the colour of the surface of the scanned object.

In the case of set 3, the input data is slightly different. Each scan contains a point cloud created on the basis of laser reflections from the surface of objects surrounding the scanner and not on the basis of determining characteristic points from images recorded by the structured light scanner. Scan processing is therefore a bit different. The processing itself and, if necessary, the control of the scanning process are carried out in the Faro Scene software (Fig. 3.7).

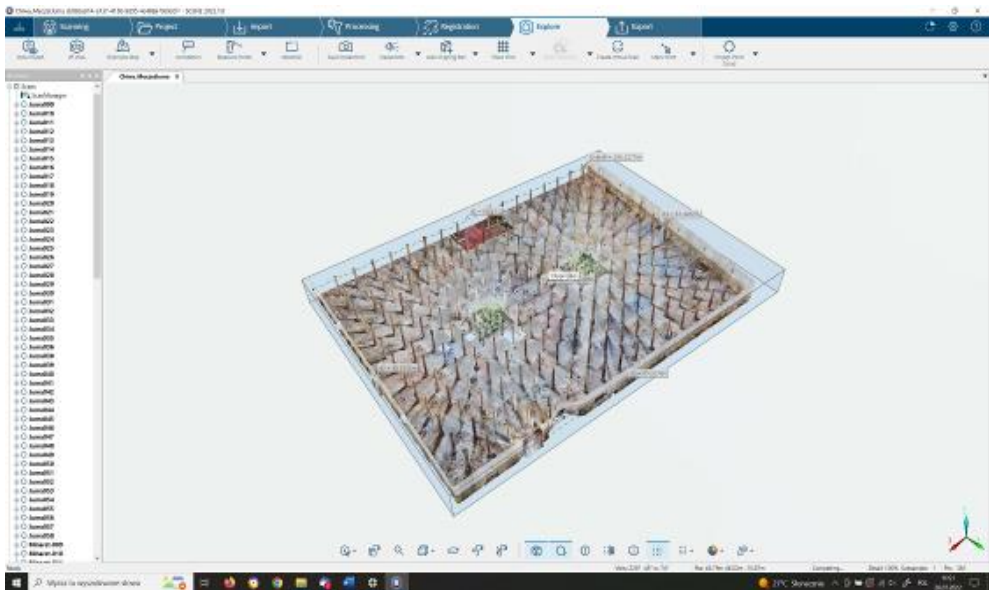


Fig. 3.7. Faro Scene window during point cloud analysis. By the authors.

The scan made at one point is one coherent whole and does not require any further adjustments of the fragments. Before the procedure of combining the scans, they are coloured on the basis of the photos taken by the scanner. As a result of colourisation, the vertices from the scan point cloud are given colours corresponding to the appropriate area in the image.

The next step is to match individual point clouds from different scans and generate one global point cloud on this basis. Only from this cloud is the mesh model generated and the colour texture created – unfortunately, the colourisation does not collect data

directly from the photos, but from the colour data of the cloud vertices in the area covered by the polygon, which negatively affects the quality of the obtained texture of the object surface. By using external software and images of the surface of the scanned object, taken with a camera, it is possible to replace the imperfect texture with an image of a much higher quality.

3.4. Summary

The 3 scanning sets presented in this chapter have fulfilled their functions and turned out to be useful when scanning Silk Road Heritage, each in a different range of objects. The possibility of using all 3 sets allowed for the scanning of virtually any object with historical value, which was selected during the project.

The diversity of hardware and software technical support is so large that it requires experience in working with each of the sets. The final effects are, however, comparable and can be used jointly, e.g. in one virtual exhibition.

The fields of application of the sets discussed overlap. The selection of the scanning method for elements on the border of using several methods depends on the available scanning conditions and the expected end results.

References to chapter 3

- [1] Miłosz M., Kęsik J., Montusiewicz J. *3D Scanning and Visualization of Large Monuments of Timurid Architecture in Central Asia – A Methodical Approach*. Journal on Computing and Cultural Heritage, 2020, vol. 14, no. 1, pp. 1–31.

4. Methodology of acquiring data of cultural heritage objects and processing the results

4.1. Interdisciplinarity of activities

Digitisation of tangible cultural heritage resources is condemned – in a positive sense – to the cooperation of people representing various scientific disciplines. The team that was created at the Lublin University of Technology included, on the one hand, people representing various humanities: art historians, archaeologists, historians and museologists, and on the other – computer scientists dealing with various types of 2D and 3D computer graphics technologies (Fig. 4.1).

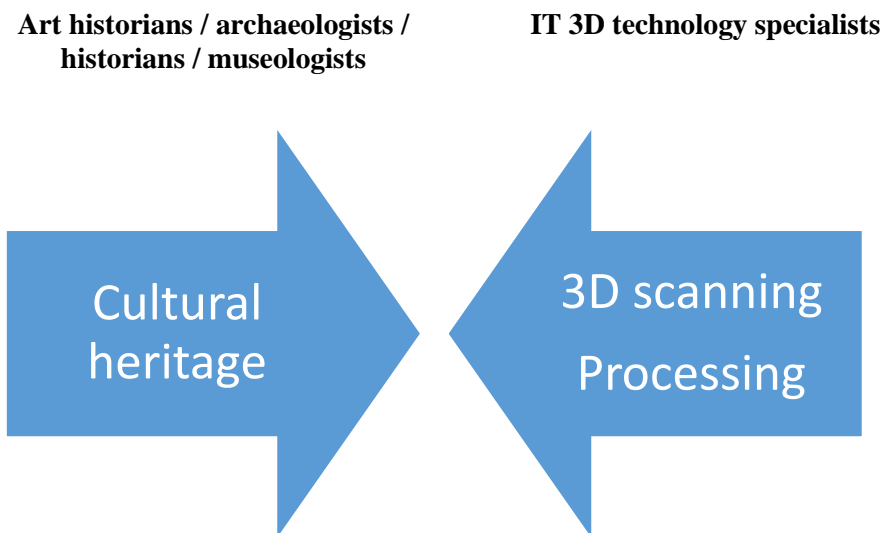


Fig. 4.1. Areas of competence and their coverage for both sides of partners. By the authors

Cooperation in such teams must be organised in such a way that both parties know exactly what tasks they are responsible for in the entire process and at a given moment. An important issue is finding the right language of communication between the two parties. This requires the mastery of new specialised terminology and concepts relating to both cultural heritage and computer technology by representatives of collaborating disciplines. The situation becomes more complicated when individual teams come from different countries, far away from each other (this limits direct contacts for online communication) and representing different cultures and religious traditions [1].

4.2. Generalised methodology of 3D digitisation of cultural heritage objects

The methodology of 3D digitisation of cultural heritage objects in general can consist of the following four stages:

- Stage 1: planning activities.
- Stage 2: in situ data acquisition.
- Stage 3: data processing.
- Stage 4: post-processing of the model.

Stage 1. Planning of activities

At this stage, it is necessary to determine what objects will be scanned, what are the terrain, premises and temperature conditions, what is the nature of the objects (e.g. in the case of transparent or shiny surfaces it is impossible to digitise them without dulling their surface, which in the case of museum artefacts is very limited or even unacceptable), what is the access to them, e.g. Can the display cases in which they are stored be opened? Can the objects be removed from them? (Fig. 4.2).



Fig. 4.2. Opening the showcase with the costume of the Emir of Bukhara in the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Uzbekistan), 2021 [2]

Stage 2. In situ data acquisition

Due to the lack of other possibilities (or their too high costs), 3D scanning of various types of cultural heritage objects must be performed in situ (in museums or architectural objects) and not in laboratory conditions. This type of action requires solving many different problems. In the case of digitisation of architectural objects in the conditions of Central Asia, a factor significantly hindering work is the excessively high ambient temperature (Fig. 4.3a). Very often it is necessary to find a suitable place to set up the scanner to change the perspective of the object observation (Fig. 4.3b).

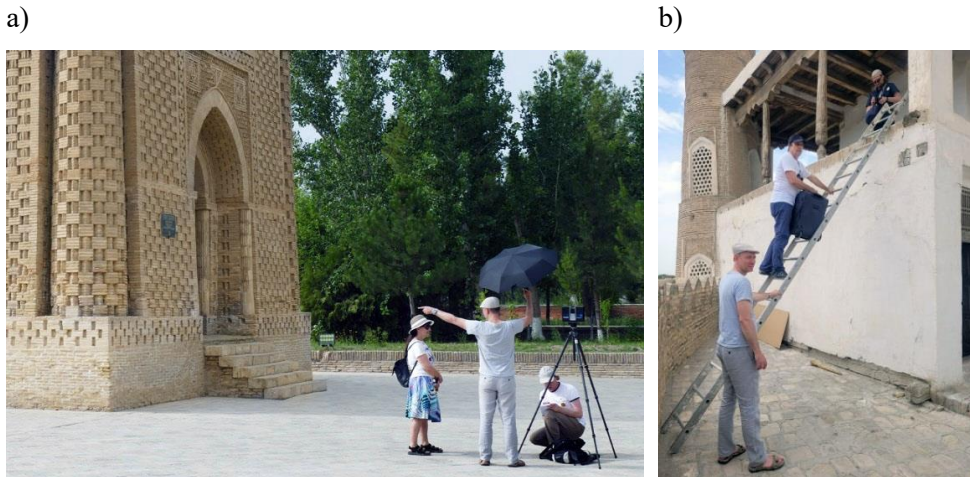


Fig. 4.3. In situ work with the FARO Focus S 350+ scanner, Bukhara, Uzbekistan, 2022, [3]: (a) shielding the scanner from direct sunlight with a black umbrella during the Samanid Mausoleum scanning, at 42° C in the shade, (b) carrying the scanner in a suitcase to the site at a balcony of the building while scanning of the Jome Mosque in Ark fortress in Bukhara

A significant problem of the digitisation of museum architectural objects is tourist traffic, i.e. people visiting the monuments intended to be scanned. This problem results from the work schedule of architectural museums (normally during the day) and the overlapping period of their 3D scanning (constant need of solar lighting). This leads to the necessity to close the facility to tourists. Unfortunately, the closure of architectural facilities to tourist traffic (both organised and individual) is usually out of the question, because visitors have purchased tickets (often well in advance) for access to the site, and tours have a scheduled period of visiting the facility. The scanning works should therefore be performed in the conditions of (sometimes very intense) tourist traffic, that attracts the attention of tourists (and disturbing activities). Tourists introduce significant disturbances to the scanning process and results. These disorders must be dealt with.

In museums, when digitising small or large objects, it is necessary to create an improvised work station with access to electricity (Fig. 4.4), or to build special structures enabling access to objects (Fig. 4.5).

a)



b)



Fig. 4.4. Data acquisition in Uzbekistan, 2022: (a) scanning the Emir's clothes, Bukhara, (b) scanning in the History of Samarkand Museum, Ulug Bek Madrasah, Registan Ensemble, Samarkand. By the authors



Fig. 4.5. Stalactite scanning at the 7 m height above the floor, 2019, Sher-Dor Madrasah, Registan Ensemble, Samarkand, Uzbekistan [4]

Stage 3. Data processing

This stage includes activities that are mainly performed after returning from a scientific expedition on specialised computer sets located in laboratories.

Processing is understood here as raw data processing, which by combining point clouds of many scans generates a mapping of the surface of the digitised object as a whole. Of course, on site, with the use of special laptops with very high computing power, trial processing of the obtained data is performed to check the quality of the work performed. This process makes it possible to repeat the scan (Stage 2) of selected site elements if necessary. Before combining scans, they are subject to process colourisation, i.e. assigning colours to points. This is done on the basis of photos of the object taken by the scanner. Connected point clouds are subject to noise reduction, i.e. removal of distortions (e.g. the view of tourists in the TLS technique) and unwanted elements (e.g. of a table surface in the SLS technique). As a result of processing, a **base cloud model** is created, containing billions of points in extreme cases (chapter 5.2).

Stage 4. Post-processing of the model

Post-processing involves many different activities, including: creating a mesh model, filling in discontinuities in the model by generating additional surfaces from triangular meshes (Fig. 4.6a). The result of post-processing is an accurate model of the object, called the mesh base model. This model is characterised by high accuracy of mapping, but also a large volume, in extreme cases reaching tens of GB. The last stage of post-processing is the reduction of the surface mesh density, i.e. the reduction of the number of triangles and thus the volume, in order to adjust the model to make it available on the Internet (Fig. 4.6b). Other activities at the post-processing stage include the preparation of omnidirectional panoramas and virtual reality files.

More advanced activities at the post-processing stage concern, for example, digital reconstruction of 3D models, which was presented in section 5.3 on the example of a jug from Afriasiab Museum in Uzbekistan, or mapping textures from external photos. In these activities, there is a need to consult with specialists representing knowledge in the area of broadly understood cultural heritage, so that the created 3D models are photorealistic and properly reflect the era from which they originated.

Post-processing of the digital model should also be performed when replication of models on 3D printers is planned. The model for 3D printing must meet the so-called condition of watertightness, which requires precise closure of all surfaces. The available programs provide functions that can do this partly automatically. The obtained model must be processed into a so-called layered model, because printing is created by adding successive fragments on the generated layers. The layer thickness (from 0.01 to 0.2 mm) determines the accuracy of the replica [6].

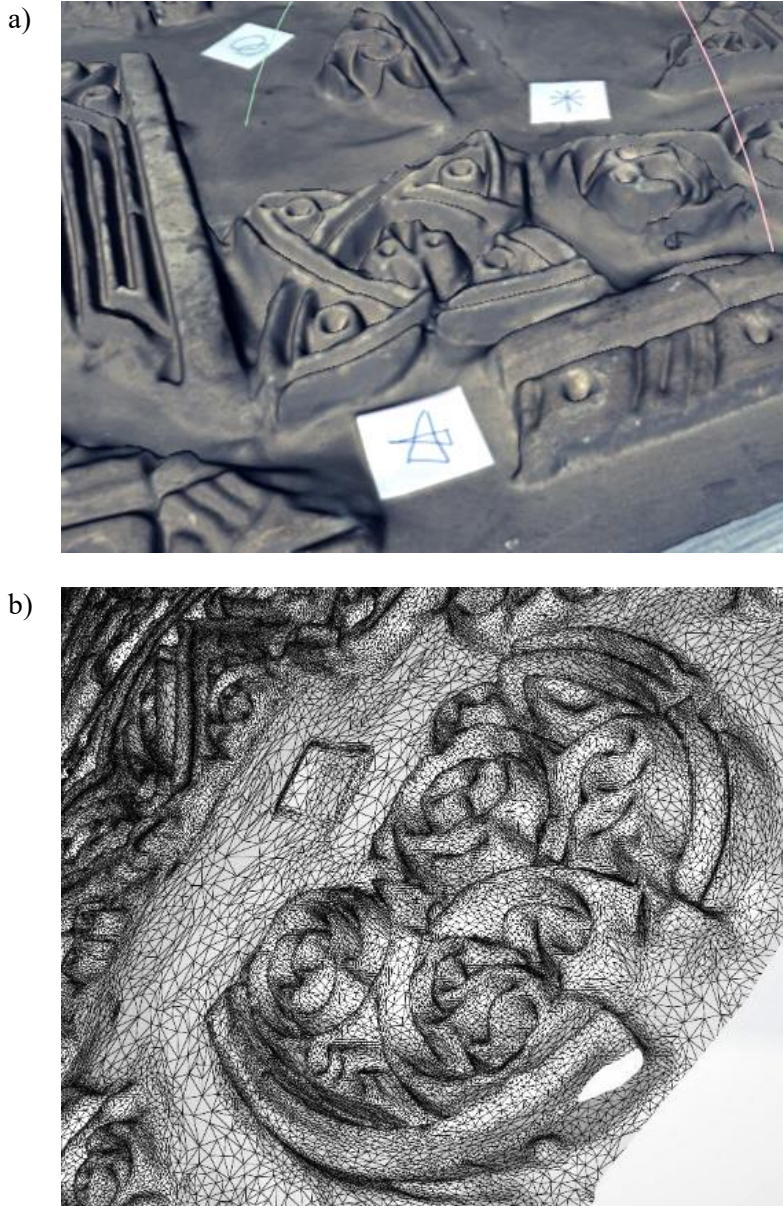


Fig. 4.6. Digital versions of objects from Afrasiab Museum, 2017, Samarkand, Uzbekistan: (a) processing in Artec Studio 12 Professional – solid model with texture, (b) post-processing in Mesh program – mesh model after reduction of the number of triangles [5]

The diagram of the generalised methodology of 3D digitisation of cultural heritage objects is shown in Fig. 4.7. This methodology usually has to be adapted to each case of the object and the 3D scanning technology used (TLS or SLS) and the device.

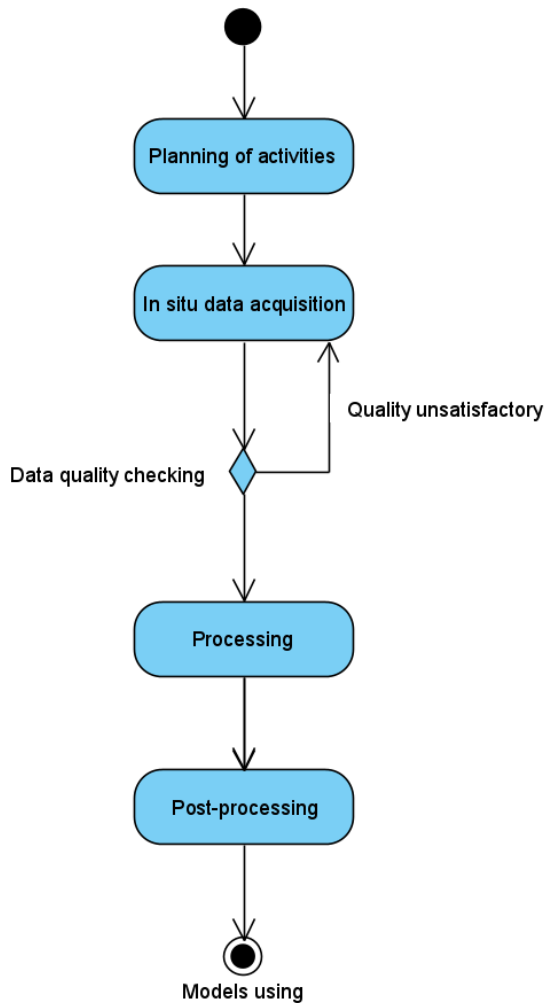


Fig. 4.7. Generalised methodology of 3D digitisation of cultural heritage objects – simplified diagram.
By the authors

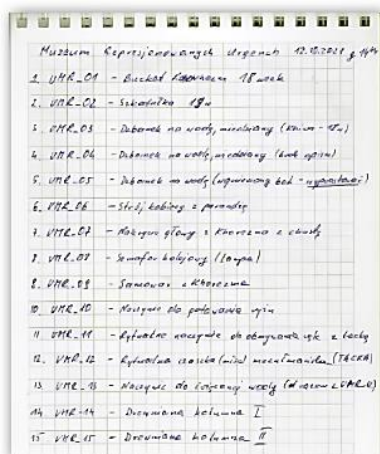
4.3. Documentation of the scanning process in situ

The 3D scanning process performed during scientific expeditions is characterised by the fact that only some of them are selected from among many museum and architectural objects. Knowledge of these objects by IT representatives is usually small, and their recognition after returning from an expedition fades quite quickly. In addition, processing and post-processing may be performed by other persons who did not participate in 3D scanning. All this makes it necessary to properly document the scanning process in situ.

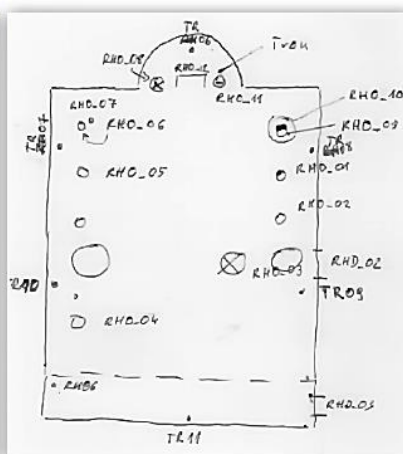
The created documentation includes descriptions, sketches, drawings, photographs and video materials. Typically, one person working with other team members should

be responsible for the descriptions and sketches. The documentation mainly contained the unique code of the scanned object, which is also transferred to the name of the folder and files generated by the scanners. In this way, all created documentation elements related to a single object are linked. The description includes the name of the scanned object (Fig. 4.8a), date and time of operation, type of scanner used, and in the case of scanners for architecture digitisation, also the location of the scanner in relation to the object (Fig. 4.8b). Object sketches are an additional illustrative element that may be useful for promoting the team’s activities (Fig. 4.8c).

a)



b)

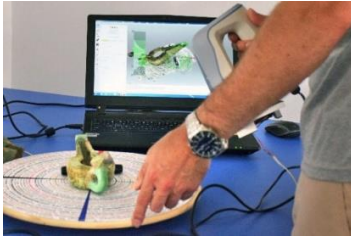


c)



Fig. 4.8. Methods of documenting, Uzbekistan: (a) a list of small items from the Museum of Victims of Oppression from Urgench, 2021, (b) a scheme of the panorama from the patio of the Pahlavon Mahmud Mausoleum, 2021, (c) a sketch of the Bibi Khanym Mosque in Samarkand, 2022 [7]

a)



b)



c)

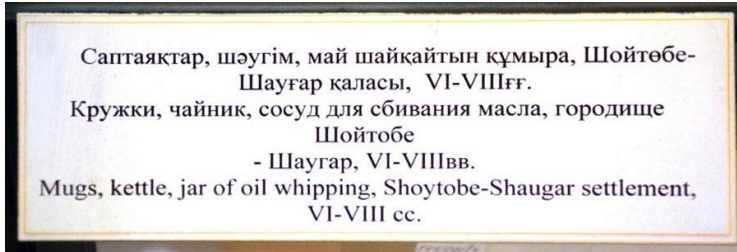


Fig. 4.9. Photographic documentation at the Ahmet Yesevi University museum, Turkestan, Kazakhstan, 2018, (a) object scanning process, (b) obtaining high-resolution texture of an object, (c) object information plate. By the authors

Photographic documentation is a very important element when performing processing. Photographing the scanning process makes it easier to link the description with the real object (Fig. 4.9a), and the photographs showing the entire object facilitate the assembly of individual point clouds into a whole, can be used to obtain textures of better quality (Fig. 4.9b), as well as to identify the object from pictures of the plates in the display cases (Fig. 4.9c).

4.4. 3D scanning methodology in intensive tourism environment

As it has been said, the generalised methodology of 3D digitisation of cultural heritage objects must be adapted to specific objects and conditions, including the IT tools used. Examples of such adjustments are illustrated in Figures: 5.3, 5.22, 5.28, 5.49, and 5.63. An important modification of the generalised methodology is 3D Scanning Methodology in Intensive Tourism Environment (3DScaMITE) [8].

This methodology has been developed and repeatedly used in the TLS digitisation of large architectural objects of the Timurid heritage on the Digital Trail in Uzbekistan and Kazakhstan [8]. These facilities are made available to tourists on a full-day and 7/7 basis. It is practically impossible to close them for several hours for scanning. No lighting or, conversely, the colourful illumination of monuments eliminates the possibility of scanning after dusk. Therefore, it is necessary to scan with tourists walking around and often approaching the scanner optics (Fig. 4.10). The detailed workflow of the 3DScaMITE methodology is presented in Table 4.1. The new sub-steps are: 1.3. Replan on site, 3.2.1. Filter and clean up data, 3.2.2. Remove or substitute problematic areas, and 3.2.3. Align partial scans.

Table 4.1. Workflow of the 3DScaMITE methodology [7]

Name of the stage	Sub-stages	Results
1. Planning	1.1. Strategic planning 1.1.1. Getting to know the archeological site 1.1.2. Selecting monuments to scan 1.1.3. Acquiring plans / photos of the monuments 1.1.4. Determining the order of scanning monuments	Sequence of monuments to be scanned – initial list of objects
	1.2. Initial planning 1.2.1. Set scanner positions and its sequence 1.2.2. Set scanner parameters 1.2.3. Set naming conventions	Final list of objects Initial plan of scanning of every object
	1.3. On-site replanning 1.3.1. Identify expected problems 1.3.2. Rearrange scan plan 1.3.3. Mark problematic positions	Plan of scanning adjusted to on-site conditions
2. Scanning	For each position: 2.1. Place and set parameters 2.2. Perform scan 2.3. Check scan quality 2.4. Mark problematic scan (if any go to 2.2) 2.5. Acquire additional data	Files with scans data Additional data (photo, historical,...)
3. Data processing	3.1. Preliminary processing 3.1.1. Process chosen scans 3.1.2. Check data quality 3.1.3. Identify scans suitable as donors (if any)	Source point clouds
	3.2. Full processing 3.2.1. Filter and clean up data 3.2.2. Remove or substitute problematic areas 3.2.3. Aligning partial scans 3.2.4. Deduplicate points	Final point cloud
	3.3. Final processing 3.3.1. Set processing region 3.3.2. Perform conversion	Base (high quality) model
4. Preparing for dissemination	4.1. Get requirements for dissemination model 4.2. Convert base to dissemination model 4.3. Test quality (go to 4.2 if needed) 4.4. Arrange dissemination model in viewing environment 4.5. Prepare/finalize model for distribution	Dissemination model



Fig. 4.10. Conditions for scanning large objects with intense tourist traffic. By the authors

The 3DScaMITE methodology was successfully used to scan large architectural objects in Samarkand, Bukhara, Khiva, Tashkent, Shahrissabz (Uzbekistan), Turkestan (Kazakhstan) and the Burana tower-minaret (Kyrgyzstan).

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5. Examples of work results

During eight Scientific Expeditions of the Lublin University of Technology to Central Asia (including one virtual), work was carried out on the 3D digitisation of cultural heritage objects of the Silk Road. Some of the expeditions were financed by the Lublin University of Technology and others by the National Agency for Academic Exchange (NAWA) as part of the “3D Digital Silk Road” project (PPI/APM/2019/1/00004).

The chapter presents the most interesting examples and their results. The work concerned the digitisation of large architectural structures (mainly mosques and madrasahs), small museum items, pieces of clothing, and even petroglyphs. Practical results of the work supported the activities of museum services and also served to popularise the monuments of the Silk Road.

5.1. The golden mosque in Tillya-Kori Madrasah, Samarkand

Tillya-Kori Madrasah in Samarkand and the Golden Mosque

Tillya-Kori Madrasah (Uzbek, ‘gilded madrasah’) in Samarkand is part of the Registan Ensemble (Fig. 5.1) – a pearl of the material cultural heritage of the Timurid dynasty on the Silk Road.

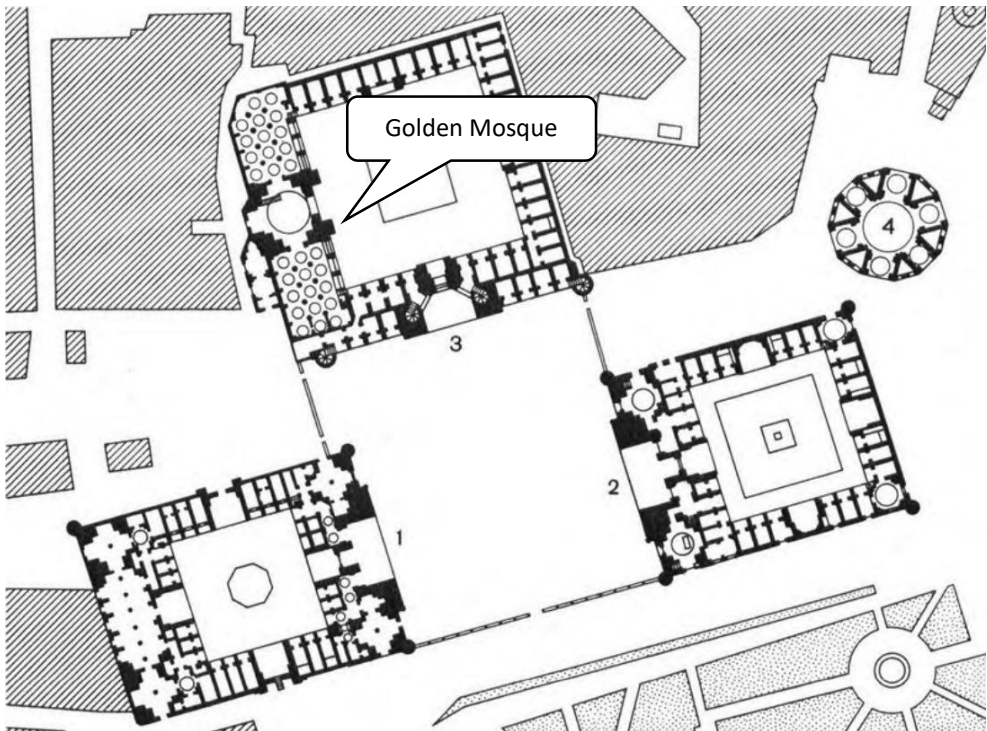


Fig. 5.1. Plan of the Registan Ensemble (3rd Tillya-Kori Madrasah). By G. A. Pugachenkova (1983)

The Madrasah was the last one built in the years 1646–1660 in Registan Square. It was built on the site of the former caravanserai, i.e. a hotel for caravans [1]. Inside the madrasah there is the Juma mosque (the so-called Friday mosque), that is the main mosque of Samarkand [1]. At that time, other major mosques in Samarkand (such as the Bibi-Khanum Mosque) were already in ruins. The mosque was built on the basis of a square that was to be covered with a double-shell dome on a circular plan. However, the outer dome of the Tillya-Kari mosque was never completed [1]. It was not until the 1970s that the outer dome of the mosque was erected during maintenance work. In 1979, the restoration work of the interior of the mosque was completed, covering the walls with kilograms of gilding. The mosque received the name: the Golden Mosque.

Objectives of activities

In 2018, during the Second Scientific Expedition of the Lublin University of Technology to Central Asia, a team of scientists from the Lublin University of Technology performed a scan of the interior of the Golden Mosque. The scanning was carried out during normal tourist traffic (closing the mosque to visitors was not an option). The scanning was carried out from the floor to obtain the dimensions and appearance of the interior of the mosque. The original goal of the activities was to create a base 3D model of the interior of the Golden Mosque and use it to archive the dimensions and appearance of the interior of the building and develop panoramas and VR contents for mobile devices in order to disseminate and share the appearance of the monument on the Internet.

At the beginning of 2019, during the preparations for the reconstruction of the outer dome of the Golden Mosque, the director of the Registan Ensemble Museum asked to provide the dimensions of the interior of the inner dome and indicate whether the base of the dome (the so-called baraban) was placed horizontally or tilted (in what direction and how much?). The data obtained in 2018 were used to analyse this problem. In 2019, the outer layer of the dome was replaced, reducing its weight by 75–80 tonnes.

Another research goal appeared. It had to be determined if the slope of the inner dome had changed after the reconstruction and by how much, as well as what was the dynamics of this phenomenon.

Performing scanning and processing of acquired data

The scanning of the interior of the Golden Mosque (including the dome) was performed in 2018 (Faro Focus X 330), 2021 and 2022 (Faro Focus S 350+). A Faro Focus scanner operating in 3D TLS technology was used. In all three scans the same scheme of setting the scanner in seven positions was used (Fig. 5.2).

The obtained data were subjected to a purification and post-processing procedure in accordance with the previously developed 3DScaMITE Methodology (3D Scanning Methodology in Intensive Tourism Environment) [2] (Fig. 5.3). The

3DScaMITE Methodology consists of four phases in three different stages of research, i.e. pre-site visit, in-situ and post-visit.

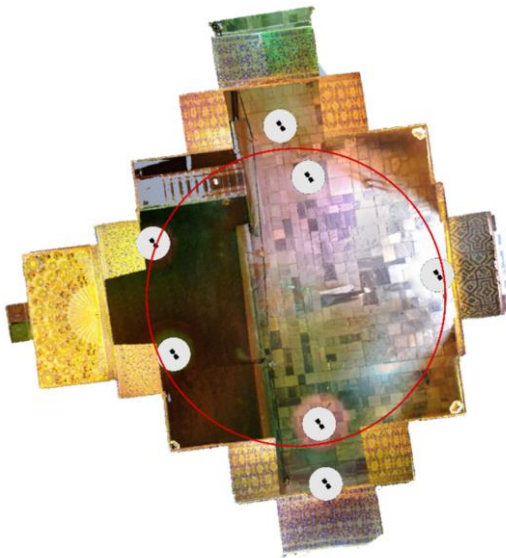


Fig. 5.2. Layout of the 3D scanner placement position in the process of scanning the interior of the Golden Mosque. By the authors

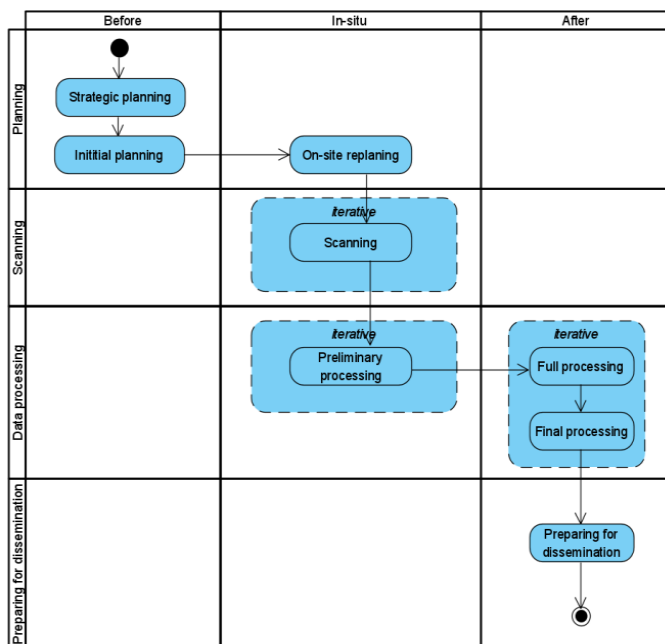


Fig. 5.3. Workflow for the 3DScaMITE Methodology. By the authors

The 3DScaMITE Methodology had to be used due to the inability to exclude the object from tourist traffic. The working conditions were not very comfortable, as shown in Fig. 5.4.



Fig. 5.4. Conditions for scanning the interior of the Golden Mosque during normal tourist traffic.
By the authors

Due to the purpose of the research, special attention was paid to the analysis of the accuracy of distance and levelling measurements by the scanner. The (non-systematic) error in measuring the distance of the Faro Focus X 330 scanner is 0.25 mm. This accuracy for the purpose of studying the geometry of large architectural objects is fully sufficient. The factory data of the Faro Focus X 330 scanner shows that the levelling error is 0.015° . With the dimensions of the base of the inner dome about 10.75 m, the horizontal measurement error is about 0.28 cm [3]. This value is fully sufficient for measurements of large architectural objects and can be neglected (the relative error in measuring the height difference between the opposite points of the base is less than 0.1%) [3].

The duration of the individual stages of the research was as follows:

- planning: 1 h,
- scanning: 1.4 h,
- data processing: 18 h,
- preparing for dissemination: 1 h.

In addition, the measurements using the created 3D models of height, inclination, etc. took about 1 hour.

After building 3D models of the interior of the Golden Mosque, measurements of the differences in the height of specific points (the upper inner surface of the base of the dome) were carried out in the axes as in Fig. 5.5, i.e. between: A1-A2, B1-B2, C1-C2 and D1-D2. The measurement scheme used for the 2018 3D model is shown in Fig. 5.5 and in a vertical section in Fig. 5.6. Analogous measurement schemes were used in the following 3D models. This ensured the comparability of the results.

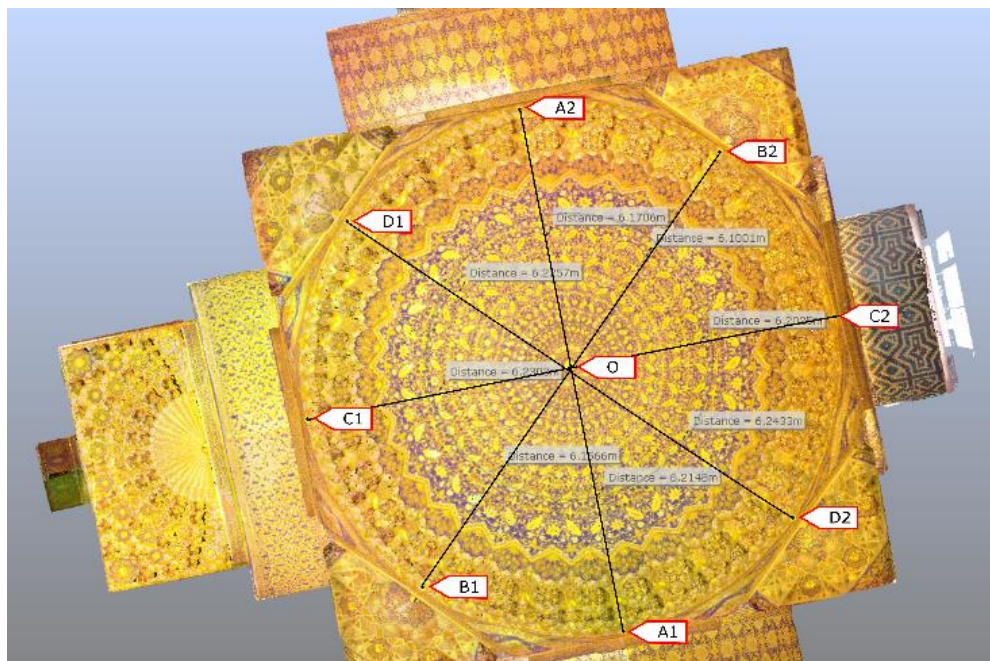


Fig. 5.5. The location of the measurement axis of the horizontal deviation of the inner dome of the Golden Mosque. By the authors

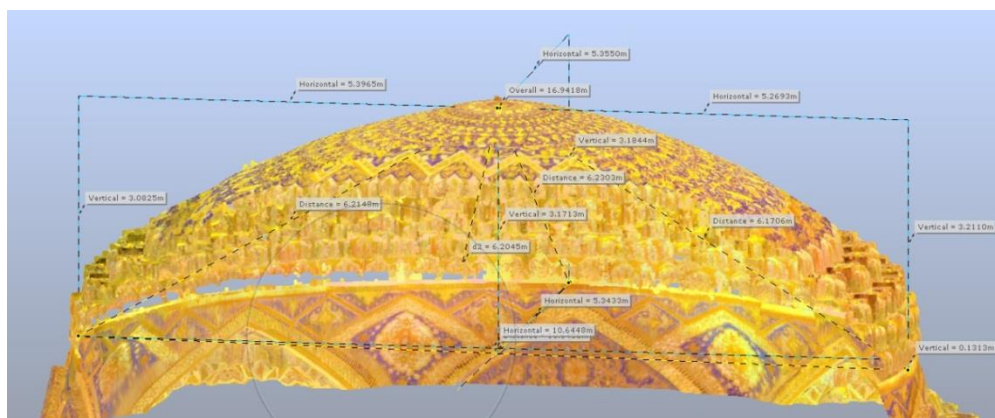


Fig. 5.6. A vertical section through a 3D model of the inner dome of the Golden Mosque. By the authors

The results

As a result of the work, it was possible to obtain data on the dimensions and appearance of the interior of the Golden Mosque. The developed basic 3D model made it possible to prepare and publicise the interior in the form of panoramas and VR contents (https://silkroad3d.com/?page_id=283).

The results of three measurements in subsequent years (i.e. 2018, 2021 and 2022) with the determination of deviations from the vertical axis of the end points of the axis from Fig. 5.5 are shown in Table 5.1. They allow the analysis of the dynamics of the tilting phenomenon of the dome base, and thus of the entire building.

Table 5.1. Measurement results

Axis	Years	Vertical differences, cm	Changes between measurements, cm	Changes per year, cm/year
A1-A2	2018	-12.37	-	
	2021	-13.37	-1.00	-0.33
	2022	-13.75	-0.40	-0.40
B1-B2	2018	-3.81	-	
	2021	-3.99	-0.18	-0.06
	2022	-4.00	-0.01	-0.01
C1-C2	2018	+10.75	-	
	2021	+11.77	+1.02	+0.34
	2022	+11.71	-0.06	-0.06
D1-D2	2018	+8.03	-	
	2021	+9.17	+0.14	+0.05
	2022	+9.17	+0.00	+0.00

Discussion

Measurements of the deviation from the level of points at the end of each axis from A to D (Fig. 5.5), carried out on a 3D model of the interior of the Golden Mosque, created on the basis of the data from 2018, showed an inclination from the level of the base of the dome along the axis A to -12.37 cm (i.e. A2 in Fig. 5.5 is lower than A1) and C at +10.75 cm and also D at +8.03 cm, Table 5.1. With a slight deviation from the B axis level, this suggests a slope of the base of the inner dome by about 23 cm (between points A2 and C2).

The dynamics of the phenomenon can be assessed by analysing the data from Table 5.1. The following conclusions can be drawn:

- dome base inclination stopped increasing in axes: B, C, and D,
- in the axes C the inclination is reversing a little,
- in the axes A the inclination increased, and the speed of the phenomenon increases.

The point A2 of the dome base (Fig. 5.5) descends and the rate (speed) of descent increases: from 0.33 to 0.40 cm/year.

Conclusions

Research has shown that 3D scanning with the TLS method is effective in large interiors. Properly planned scanner placement points allow to obtain data on the dimensions and appearance of even complex interiors.

The acquired data can be used to create 3D interior models, including panoramas and VR contents.

The stored archival digital data can be used for various purposes, including research and measurements of the object geometry without the need to carry out on-site measurements, which is difficult with such large objects and requires the use of specialised equipment (e.g. lifts or scaffolding).

3D scans performed several times at intervals make it possible to perform a comparative analysis of the building geometry over time. This allows to analyse the dynamics of various phenomena.

5.2. Juma Mosque in Itchan Kala (Khiva) – interior

Juma Mosque in Itchan Kala

The Juma Mosque (literally “Friday Mosque”) was built between the 10th and 18th centuries in Khiva, Uzbekistan [4]. It is located in Itchan Kala, the old part of the city of Khiva, surrounded by fortified walls. The Juma Mosque has been inscribed on the UNESCO World Heritage List. It was built in the centre of Itchan Kala, on the east-west road (from the eastern gate of Polvon darvoza to the western gate of Ota darvoza). The mosque was first documented in the 10th century, but has been damaged throughout history. On the orders of Abdurahman Mehtar in 1788 it was rebuilt and at the same time altered. The Juma Mosque is characterised by a unique style and size – the building without portals and domes, without cloisters and courtyards (Figs. 5.7 and 5.8).

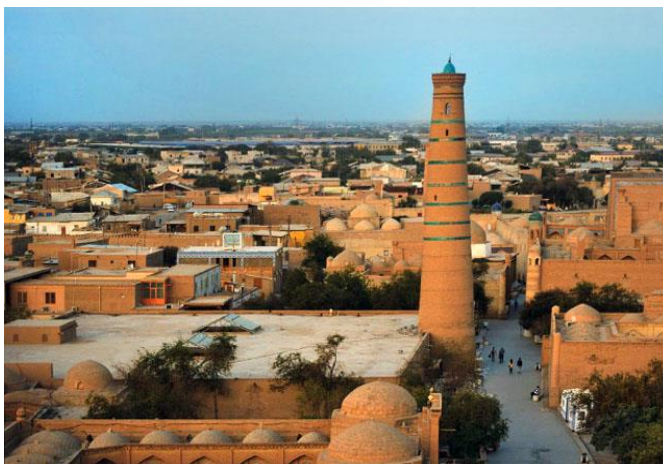


Fig. 5.7. Juma Mosque with a minaret [5]

The internal structure of the Juma mosque is based on a rectangular plan with dimensions of 56x43 m (others say: 55x46) and a height of 4 m. The wall from the side of the Kalta Minor minaret is slightly cut, resulting in a rectangular trapezoidal room with a total hall area of approximately 2370 m² (Fig. 5.9).

a)



b)



Fig. 5.8. Juma Mosque, interior: (a) fragment of the hall with a skylight, (b) mihrab. By the authors



Fig. 5.9. Juma mosque plan, 3D scanning point cloud preview. By the authors

The only natural source of light in the mosque are 2 roof windows, 5x5 m in size, and a skylight above the mihrab [4]. The wooden roof is supported by 213 wooden columns evenly spaced in the form of a square mesh with an eye spacing of 3.15 m. The vast majority of the columns are carved with individual patterns containing

geometric and floral ornaments (trees, shrubs, irises) and inscriptions in the Arabic alphabet. The sculptures differ in the depth of the pattern, and on some of them specific dates can be found: 1316, 1510, 1788, 1789, which is interpreted as the years of the mosque construction/expansion stages (Fig. 5.10).

a)



b)



Fig. 5.10. Architectural details of the columns: (a) floral ornaments on the column, (b) column head with a wooden ceiling. By the authors

The age of the columns is varied and ranges from the 10th to the 21st century [5]. Hence, it is often believed that the Juma Mosque looks almost like a museum depicting the history of traditional wood carving of the Khiva Khanate and is considered the most original and unique mosque in Uzbekistan.

Objectives of activities

In 2021, during the Sixth Scientific Expedition of the Lublin University of Technology to Central Asia, a team of scientists from the University performed a scan of the interior of the Juma mosque. The scanning was carried out during normal tourist traffic. The scanning took place basically from the floor (the scanner was standing on a tripod about 50 cm above the ground) and was aimed at obtaining the dimensions and appearance of the interior of the mosque.

The main goal of the activities was to create a base 3D model of the interior of the mosque. The collected data were to be used to archive the dimensions and appearance of the interior of the building. In addition, it was planned to develop panoramas and VR contents for mobile devices so that it would be possible to disseminate and share the appearance of the site on the Internet.

Carrying out the scanning and processing the acquired data

The Faro Focus S 350+ scanner was used to digitise the interior of the Juma mosque in 3D. Due to the different sculpting of the columns, it was important to capture the carvings around the entire circumference of the column. It was necessary to position the scanner to scan each column from 4 sides, however, arranging the columns in the form of a square grid complicates the positioning of the scanner due to the fact that the columns obscure each other.

The shape and decoration of the columns, where a significant part of the carving is located in the lower part of the column at a significant angle of inclination in relation to the length of the column (Fig. 5.11), creates additional problems when positioning the scanner – a typical placement of the scanner on a tripod at a height of approximately 2 m from the ground would make it impossible to scan the bottom of the columns.

One of the most important elements of the mosque are its columns with an individual, unique shape. When making a 3D scan of the interior, it was necessary to ensure that the columns were scanned with satisfactory accuracy. The Faro Focus S 350+ scanner used worked in the “interior HDR” mode and reduced noise correction. In this way, the scanner operation time was limited with the moderate intensity of tourist traffic forecast (no need for a significant correction). In the case of too many tourists, taking pictures was repeated or the entire scan was repeated sporadically.



Fig. 5.11. The shape of the columns in the Juma Mosque – point cloud after multiple partial scans.
By the authors

The specificity of the TLS scanner operation means that the most accurately scanned areas (with the most scanned points per unit area of an object) are perpendicular to the scanner. The scanning density decreases as the surface deviates from the perpendicular position to 0 in the parallel position ($\pm 90^\circ$). The scanning density is also strongly dependent on the distance from the scanned surface (the closer to the scanned surface, the greater the density of the measurements). The columns to be scanned are generally cylindrical and covered with grooves. By analysing the density and depth of the grooves it was found that a satisfactory scan density of the column surface could be obtained when the scanner was positioned no more than 6 m (two column spacing lengths) from the scanned column. In order for the entire circumference of the column to be scanned with a uniform density, it was necessary to perform at least 4 scans arranged in successive quadrants around the column (Fig. 5.12).

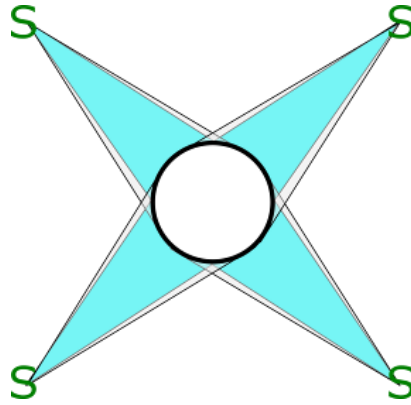


Fig. 5.12. Display of column surface coverage with scans from four scanner positions (S). Grey – the surface of the column “seen” by the scanner, blue – surface with an acceptable scan quality.
By the authors

A scanner positioned in the center between the four columns scans one surface for each one. Direct application of our observations would require about 250 scans (number of fields between columns + positions outside). The duration of such a session and the amount of data collected would exceed the possibilities available during the scientific expedition.

While analysing the blind spots (areas obscured during scanning), it was noticed that after the elimination of the scanning in every other field between the columns, the resulting shortages are compensated for from the remaining scanning positions in the adjacent rows/columns, and being at a distance falling within a predetermined limit 6 m (Fig. 5.13). Thanks to this solution, the number of necessary scans was reduced to 128.

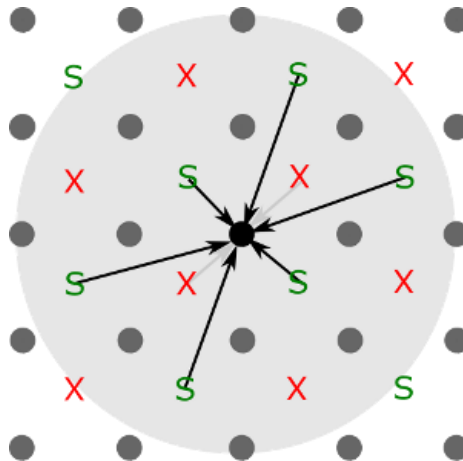


Fig. 5.13. Visualisation of the visibility of the column by the scanners in successive positions (S) and the possibility of eliminating the position (X). By the authors

The problem of scanning the rounded bottom of the columns was solved by using a low position of the tripod – about 50 cm above the floor (Fig. 5.14).

The scanning was carried out on October 21 and 22, 2021, during the 6th Scientific Expedition of the Lublin University of Technology to Central Asia. The total scanning time was 13 h 39 min. and was carried out in rotation manner by a team of 6 (at least 2 people were always present to verify the order in which the scans were performed). A single scan took about 6 minutes, including the time it took to move and position the scanner.

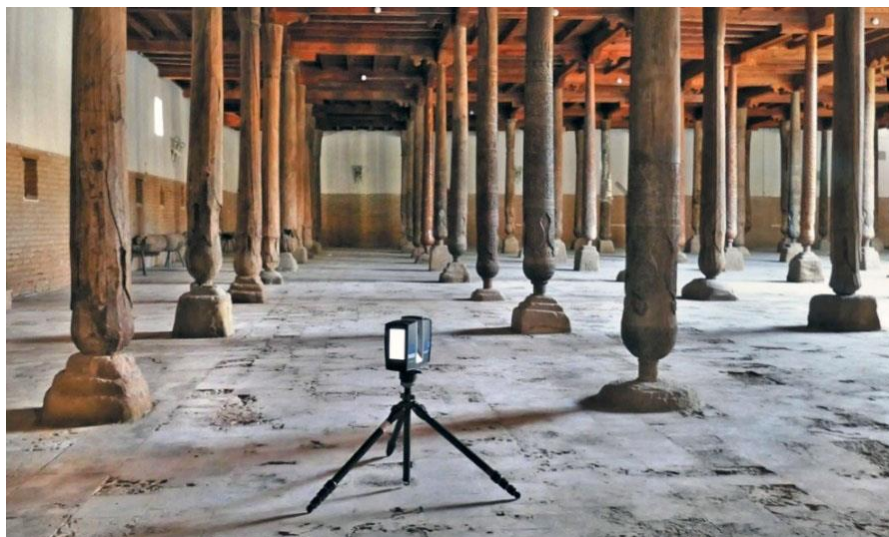


Fig. 5.14. The 3D scanning process of the Juma mosque using the Faro Focus S 350+ scanner.
By the authors

The scanning was carried out during the normal operation of the mosque/ museum, which meant a constant movement of tourists and pilgrims. The role of the team was therefore also to prevent tourists from entering the 6-meter area around the scanner while the device was operating. Due to the sacred nature of the object, it was also necessary to introduce a few short breaks in scanning for the time of prayers.

The results

The end result of the scan within 2 working days was the acquisition of 27.5 GB of raw data.

The procedure of processing and positioning individual scans required the use of specialised software and a computer with significant computing resources (16-thread Intel I9 processor, 64GB of RAM, high-performance NVIDIA RTX2080 graphics card) and consisted of several basic steps:

Stage 1

Colouring the scans. This stage took 2 hours with the computer running at full load. After this stage was completed, it was possible to visualise individual scans in colour and their clouds of coloured points in the 3D space (Fig. 5.15).

a)



b)

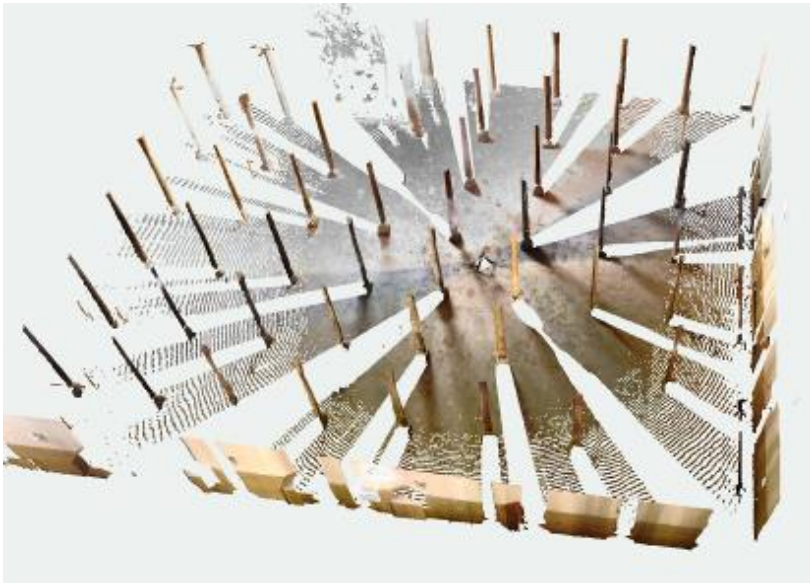


Fig. 5.15. Single scan view of the Juma Mosque: (a) image captured by the scanner, (b) view of the registered 3D point cloud. By the authors

On the example of this scan, the correctness of the applied system of scanning places can be observed. The areas of visible columns from the primary and secondary groups are as assumed in the earlier estimates (Fig. 5.16).

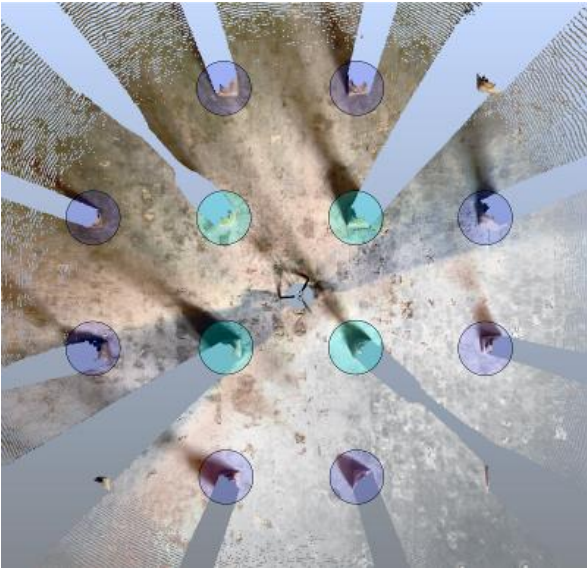


Fig. 5.16. Scan result confirms that all required column surfaces are visible. Green – column surfaces in the primary zone, blue – column surfaces in the secondary zone. By the authors

Stage 2

Adjusting the scans to each other (which took about 1 hour), and creating a uniform point cloud (3 hours of computer operation). The resulting point cloud had a size of 2 billion 182 million points (Fig. 5.17).



Fig. 5.17. Merged point cloud view. By the authors

This cloud contained unwanted artefacts recorded by individual scans resulting from the tourist traffic in the mosque during the scan (Fig. 5.18).

a)



b)



Fig. 5.18. An example of the occurrence of unwanted artefacts – people visiting the facility: (a) photo during 3D digitisation, (b) image recording from a 3D scanner. By the authors

Stage 3

Cleaning the scans of unwanted artefacts resulting from the necessity to perform scanning during the daily tourist traffic. The procedure of removing noise from the scanner records took over 4 hours of work. The end result was obtaining a merged point cloud cleared of unwanted elements (Fig. 5.19).



Fig. 5.19. View of the cleared point cloud after 3D scanning of the Juma Mosque. The mosque ceiling has been hidden to reveal the interior. By the authors

Stage 4

Activities under this stage included the development of omnidirectional panoramas of the interior of the Juma mosque and the preparation of the object for VR contents. For technical reasons (hardware and software), they could not yet be implemented.

Discussion

Hardware and software performance problems resulting from processing such a large number of scans (132), will become less important as more and more efficient computer hardware and more advanced algorithms develop.

Conclusions

The process of data acquisition during long field trips should always be carefully thought over, and the work carried out should be subordinated to a defined main goal.

Limited time and equipment resources (duration of the expedition, number of objects to be digitised, number of scanners, etc.) force us to accept certain compromises between the implementation of the tasks set for ourselves and the quality of the digitisation process.

The selection of the parameters of the 3D scanning process is a very important issue, because it determines the time of data acquisition and its accuracy. However, you need a lot of knowledge to be fully clear how this affects the post-processing process and the quality of the complex model.

5.3. Digital reconstruction of museum objects

A ceramic vessel from Afrasiab

The water-carrying jug at the Science and Practice Museum-Laboratory of Samarkand State University (SamSU) in Uzbekistan was digitised by the authors in 2017 during the First Scientific Expedition of the Lublin University of Technology to Central Asia. These were the first scans of historic artefacts of this museum (Fig. 5.20). The scanning process allowed for the creation of a 3D mesh model of the jug and the execution of appropriate measurements (Fig. 5.21).



Fig. 5.20. The 3D digitisation process of the jug using the Artec Spider scanner. By the authors

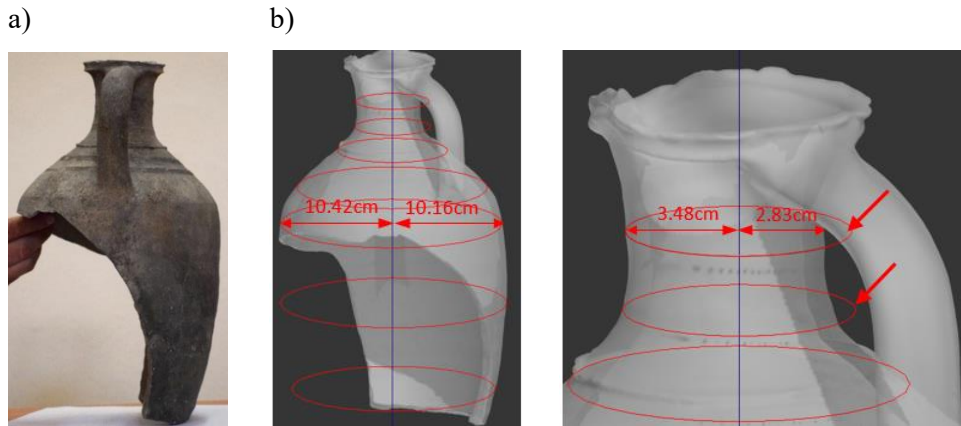


Fig. 5.21. Afrasiab jug: (a) real object, (b) dimensioning of the mesh model. By the authors

The 12th century jug from the ancient city of Afrasiab (now a district of Samarkand), destroyed by Genghis Khan in 1220 [6], was badly damaged. The part with the spout and ear has been preserved, most of the side wall and the bottom are missing.

Objectives of activities

Contemporary museums are interested in reconceptualising their exhibitions and functioning in order to create new relationships with visitors and provide them with content and information about the collected artefacts in a new, more attractive way [7]. Such activities can be carried out using the digitisation of selected objects of their collections.

The original goal of the activities was to prepare digital 3D models of museum artefacts for dissemination on the Internet. Later, further research targets emerged. One was the development of procedures enabling digital reconstruction of the entire object by recreating its missing fragments on the example of damaged ceramic vessels available in the form of 3D mesh models. In addition, there was the preparation of methods for collecting and generating missing textures, and then mapping them on the reconstructed surfaces of the object. The activities performed also concerned the selection of software and tools as well as file formats for importing and exporting objects at individual stages of the implementation of tasks.

Methodology of surface reconstruction of 3D models of axisymmetric objects

Several methods are known today that can be used to perform digital reconstruction of museum or archaeological objects. One of the methods copies similar elements/fragments of an object, and then after adjusting them (scaling, rotation, displacement, mirror), they are placed in the appropriate place of the reconstructed object [8]. Another way is to find in the digital database of signatures the curvature of vessel fragments that are identical to the vessel, which allows to determine its original shape [9]. This method cannot be used as there are no data gathered on the basis of collections from the territory of Uzbekistan. The authors present their own approach, which was partially presented in [10].

Stage 1. Obtaining a digital representation of the 3D model

The 3D scanning and post-processing procedure shown (Fig. 5.22) leads to a digital mesh model which has been exported to an .obj file. Thanks to this, information about both the surface geometry and colour and texture is stored (.stl format only stores geometry). In the .obj format, the geometry of an object's surface is described by: polygons, Bezier curves and NURBS surfaces. This format ensures seamless file exchange between graphics applications, minimising the risk of errors.

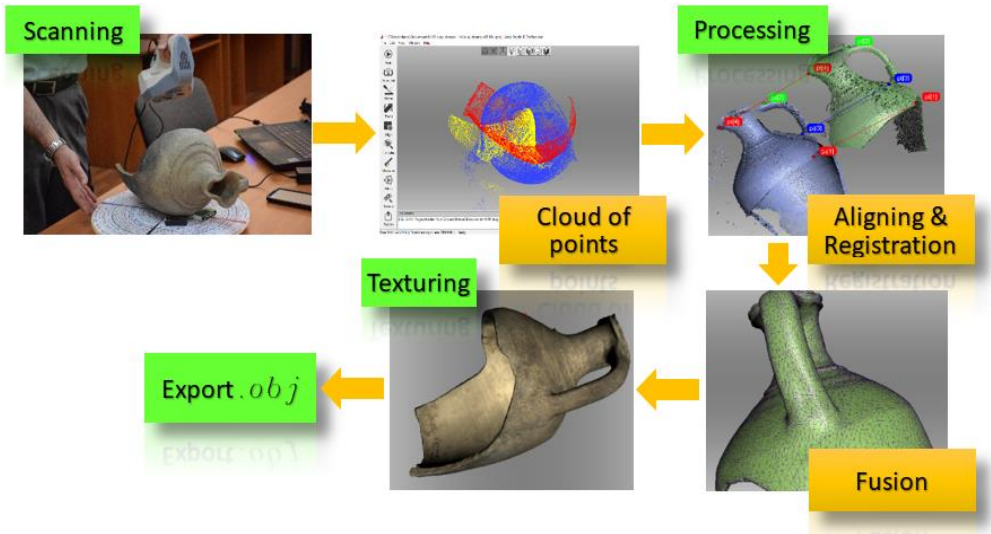


Fig. 5.22. Visualisations of activities – from a real object to a digital mesh model with a mapped texture saved in .obj format [10]

Stage 2. Geometric reconstruction of the 3D model

The 3D model geometry was reconstructed in the 3ds Max program. After importing the 3D model in .obj format to the program, the following actions were performed:

- adjusting the orientation of the object so that its alleged axis of rotation runs along the vertical axis of the coordinate system,
- determining the axis of symmetry of the digital model according to the following procedure
 - determining the indicative axis of rotation a_0 for the entire vessel,
 - generation of p_i planes perpendicular to the a_0 axis with a constant pitch value,
 - determination of o_i circles formed by the intersection of the p_i planes with the digital image of the vessel,
 - determining the measures c_i for all districts o_i ,
- calculation of a new vessel rotation axis a_k by adjusting the centres of circles c_i using minimisation of differences in the position of individual centres c_i with respect to the position of the axis of rotation a_0 on the analysed plane p_i :

$$a_k = \min \sum_{i=1}^n \omega_i \cdot \sqrt{(a_{o_i}^x - c_i^x)^2 + (a_{o_i}^y - c_i^y)^2} \quad (5.1)$$

where:

- ω_i – weight of the calculation validity for each p_i plane,
- $\omega_i = 1$ – when we obtain a full circle for the p_i plane,
- $\omega_i < 1$ – for the remaining cases, the greater the value, the greater the length of the resulting arc.

- creating the outline of the vessel (Fig. 5.23a),
- recreating the created outline three times, each of which was rotated relative to the axis by angles of 90° , 180° and 270° , respectively (Fig. 5.23b),
- modification of copied contours to digital surfaces created after scanning,
- generating the missing surfaces by circling the copied contours (Fig. 5.23c) – this process also fills the interior of the object,
- removing the interior of an object by applying the Boolean algebra operation (the subtracted object is smaller to obtain the correct thickness of the vessel wall).

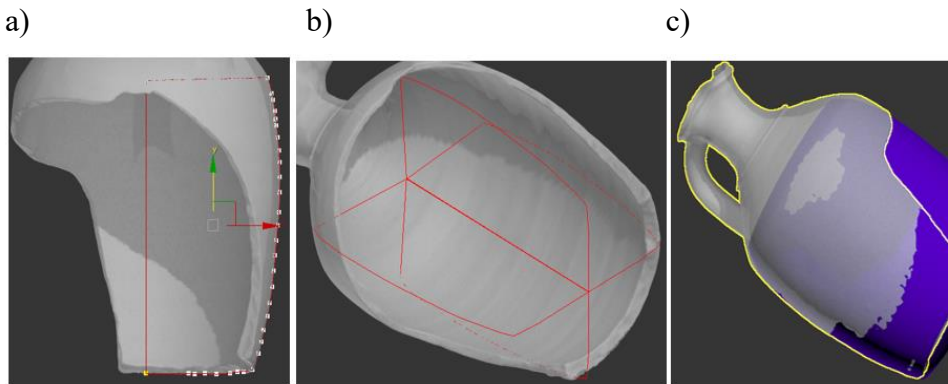


Fig. 5.23. The reconstruction stages: (a) single contours, (b) three times enlarged and rotated outlines, (c) generated 3D model [10]

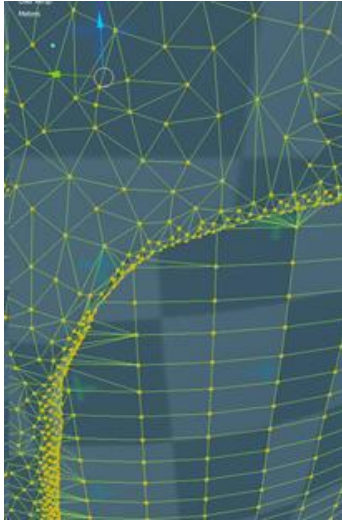
Stage 3. Reconstruction of the texture of the 3D model

Proper mapping of textures on the surfaces of the digital model allows to obtain the photorealism effect of a digitally reconstructed 3D object and to some extent mask the defects of the geometric 3D model. The free Blender program was used for the texture mapping process.

The developed procedure consisted of the following steps:

- loading a reconstructed 3D model and building a scene containing lighting and cameras,
- smoothing the contact points of different types of meshes – the meshes from scanning are triangular, while the generation during reconstruction is quadrilateral (Fig. 5.24a),
- generating and applying a UV texture to a 3D model (Figs. 5.24b and 5.24c).

a)



b)



c)

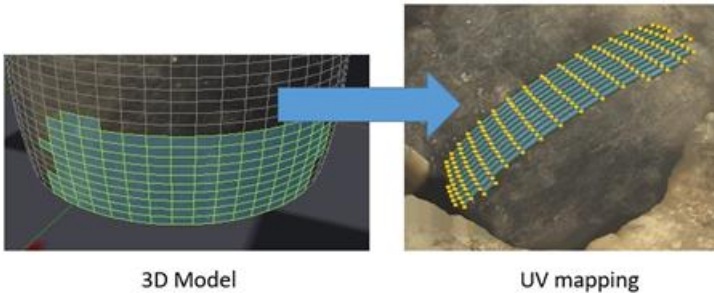


Fig. 5.24. Preparation for texturing: (a) place of connecting the original artefact and reconstructed meshes, (b) UV texture applied to the model, (c) UV mapping made in the Blender program.
By the authors

The results

The performed works led to the generation of a complete geometric digital 3D model (Figs. 5.25a and 5.25b). There are clear differences in the mesh model after the summation operation (Fig. 5.25a) – the original model mesh generated after processing data from 3D scanning is very complex and irregular, and the 3D mesh of the reconstructed model – in this case, we have a regular and significantly simplified mesh (quad mesh).

The use of the procedure for creating and mapping a texture on a digital 3D geometric model brought the expected results (Fig. 5.25c). The uniformity of the texture, without distortions, gives a positive impression to the person viewing the model. There is no artificiality in the presented model.

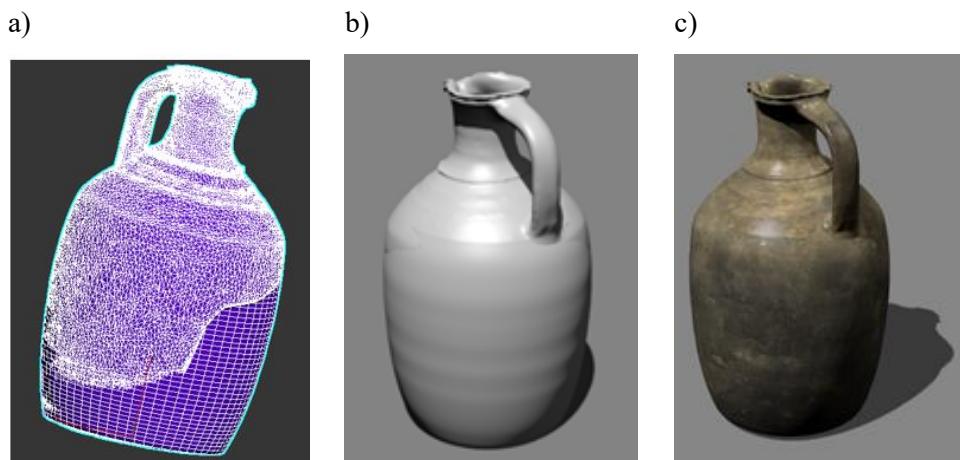


Fig. 5.25. A jug with a reconstructed part: (a) in the form of a 3D mesh model, (b) after rendering without texture, c) after rendering with texture. By the authors

Discussion

An important issue for the obtained final reconstructive effect of the object is the area of connection of the mesh consisting of triangles (created after 3D scanning) with the quad mesh (generated after applying reconstruction procedures), because there are texture deformations there when mapping them.

The work uses a solution based on the decomposition of the mapping process into smaller areas. This solution gives the expected results, but requires more work and time.

Conclusions

Obtaining a complete 3D digital object of a jug with an applied texture proves that the developed and applied procedure was correct and worked well on the presented example.

The digital reconstruction of vessels from excavations requires the cooperation of specialists in the field of computer technologies of 3D graphics and archaeologists/museologists. In a specific example, the analysis of the preserved fragment of the vessel lacked information about the location of the bottom of the pitcher. Consultations with specialists allowed us to obtain a complete digital vessel with the right proportions between its diameter and height.

Reconstruction of axially symmetric vessels can lead to the generation of digital 3D models that will be clearly artificial. This situation occurs when the missing vessel shape is reproduced by rotating the vessel outline with respect to its axis of symmetry. Note that creating vessels on a potter's wheel never creates perfectly symmetrical objects, as shown in Fig. 5.21b.

5.4. Petroglyphs in Hodjikent

Rock Drawings in Northeast Uzbekistan

In the years 1949–50 H. Alpysbaev discovered petroglyphs on rocks in the upper reaches of the Chirchik River [11]. He discovered images of ibexes, human beings and other undefined figures on cliffs next to the village of Hodjikent (also known as: Khodjakent, Khojakent or Khojikent) located about 75 km from Tashkent (Fig. 5.26). The discoverer of the 23 images dated them to the 1st millennium B.C. [11]. In 1980–83 the site was investigated by M. Khujanazarov, who discovered another 90 separate paintings and entire scenes in the area. Petroglyphs presented “ibexes, orgolis, deer, solitary bulls, dogs and uncertain symbols” [11]. They were made in the 4th millennium and the first half of the 3rd millennium B.C. [12].

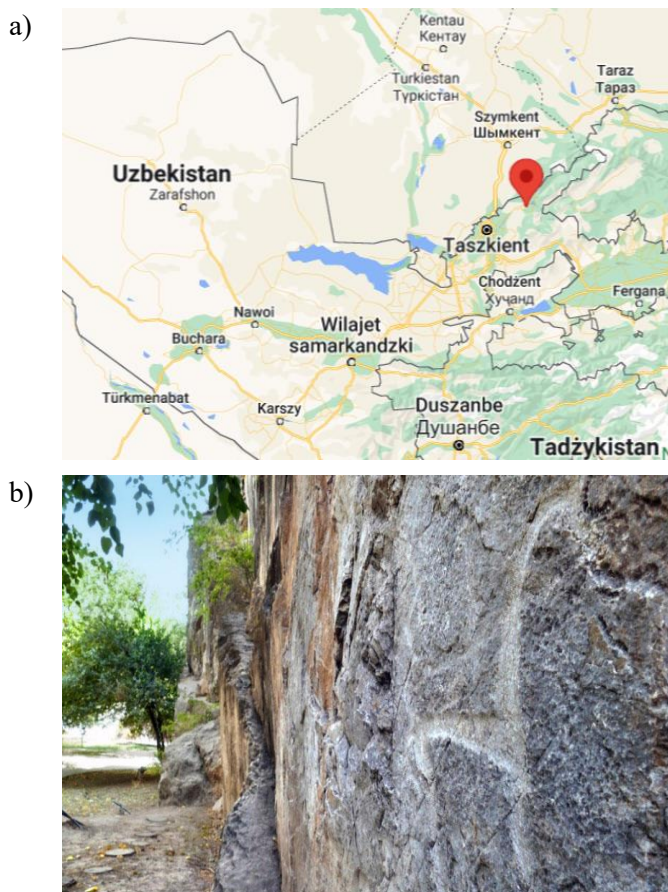


Fig. 5.26. The location of the village of Hodjikent and the petroglyphs on the Cliff:
(a) by <https://www.google.com/maps/>, (b) by the authors

Objectives of activities

Many of the petroglyphs in the village of Hodjikent are situated in a generally easily accessible place, 20-30 meters from the asphalt road. They are at high risk of vandalism and are not protected against the influence of weather conditions. The weather conditions in this mountainous part of Uzbekistan are unfortunately quite harsh: in winter it is snowing and temperatures drop below -20°C , in summer reaching $+50^{\circ}\text{C}$. Due to the dry climate in summer, large temperature drops are observed at night. In winter, however, there is a lot of snowfall, which leads to its accumulation on the slopes of the mountains. With rapidly rising air temperature in the spring, this causes large streams of water running down from the mountains.

During the 6th Scientific Expedition of the Lublin University of Technology to Central Asia, measures were taken to ensure:

- field verification of the methodology and equipment for scanning petroglyphs using 3D SLS,
- development of basic 3D petroglyph models,
- scientific use of the developed base 3D models,
- popularisation of three-dimensional petroglyphs on the Internet.

Methodology and implementation of works

The planned work includes the use of an SLS Artec Eva. Due to the work in the field, the scanner was powered by a battery power supply with a capacity of 59.2 Wh. The MS Surface Pro 7, i7, 8GB RAM tablet was selected as the data logging device. During the work, various software was used, such as Artec Studio version 12 Professional (dedicated to Artec scanners) and 3ds Max by Autodesk.

The works were carried out in one day without additional technical preparation (such as scaffolding or a lift) in quite difficult field conditions (Fig. 5.27).



Fig. 5.27. Scanning petroglyphs in the village of Hodjikent. By the authors

The work uses a modified scanning and post-processing procedure (Fig. 5.28). On the one hand, the modification was forced by the lack of information about the facility necessary for the initial planning of activities. On the other hand, the team had no experience in scanning with a given hardware configuration in conditions of power unavailability. It was necessary to configure a new hardware and software set, unchecked in in-situ scanning. For this reason, activities related to “Collection of equipment and its verification” (Fig. 5.28) were introduced into the workflow, and the planning tasks were supplemented with inspection and planned in-situ. The methodology used (Fig. 5.28) consists of four phases (Preparation, Planning, Scanning and Data processing) at three different stages of the study, i.e. before the site visit, in-situ and after.

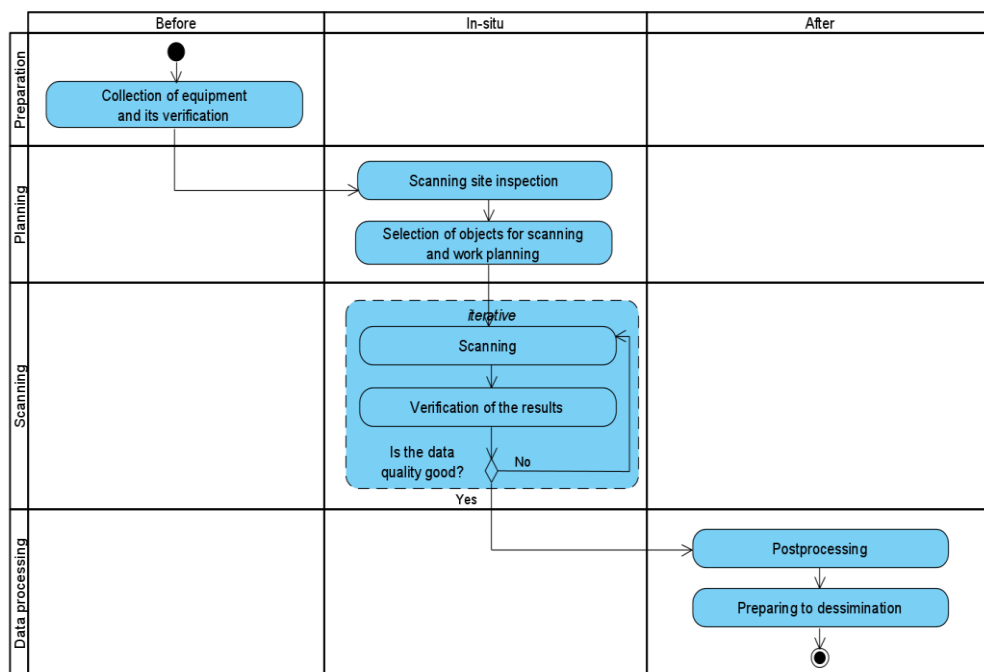


Fig. 5.28. Petroglyph scanning workflow. By the authors

Results and their use

Scanning in the field with the use of configured equipment allowed to obtain data on the geometry and appearance of 9 petroglyphs from the village of Hodjigent (Fig. 5.29). About 6 GB of data was obtained in .zip format.

During the work, the correctness of configuration and initial performance calculations (including mobile operation times) of equipment for scanning, verifying and recording data in-situ in the conditions of no access to power from the power grid was checked in the field.

Base models of 3D scanned petroglyphs (Fig. 5.29) were also developed for use in future work.

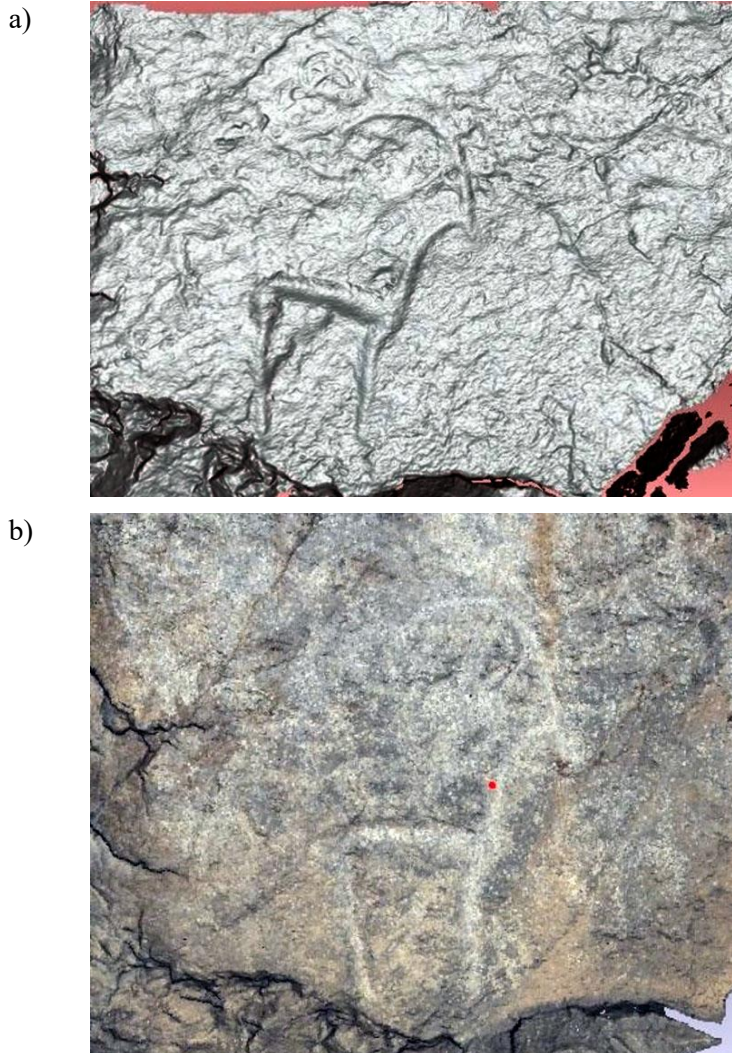


Fig. 5.29. Digital visualisation of an ibex-shaped petroglyph: (a) acquired point cloud, (b) petroglyph base model. By the authors

3D base models made it possible to develop highlighting algorithms for petroglyphs in order to present them more effectively in the digital space [12].

The base models were used to develop a 3D presentation of petroglyphs on the Internet: https://silkroad3d.com/wp-content/web3DView/5_CA/Petroglyph/?desclang=EN&prev_page_id=2717

Conclusions

The developed methodology, configuration of SLS hardware and software allowed to efficiently carry out 3D scanning of petroglyphs in Hodjikent. During an almost day of work, in the absence of power supply from a constant electrical network, it was possible to scan 9 petroglyphs in 3D. The methodology was used, and the results confirmed its correctness.

Base 3D models of selected petroglyphs allowed for further actions:

- eternal archiving of the geometry and appearance of selected petroglyphs in Hodjikent,
- developing algorithms for highlighting petroglyph patterns [13],
- development of simplified models for presentation on the Internet.

5.5. Collection of Uzbek headgear

Tubiteykas – traditional headgear in Uzbekistan

Tubiteykas are traditional caps of Muslims from Central Asia, which are worn by many representatives of different nations not only on holy days, but also on a daily basis. Tubiteykas differ significantly for individual regions and countries, and from their shape, execution, decorations and ornaments placed mainly by embroidery, but also with the use of beads, embossed plaques or sequins (in modern versions, also by printing plastic mass), one can recognise their place of origin. In modern Uzbekistan, tubiteykas are quite commonly worn by both men and women (Figs. 5.30–5.32).



Fig. 5.30. Tubitejkas from the mid-nineteenth century, Integrated Museum of Historical and Architectural and Samarkand Art. By the authors



Fig. 5.31. Tubiteykas today worn by men. By the authors



Fig. 5.32. Tubiteykas currently worn by women. By the authors

Tubiteykas are made of soft materials based on wool, felt or stiffened fabrics of various textures. Most of those occurring in Uzbekistan have a shape resembling a cylinder covered with a tetrahedral pyramid of very insignificant height (Figs. 5.31 and 5.32). Objects from the nineteenth century are usually pyramids standing on prisms with an octagonal base or shape similar to cones, bowls or quadrilateral pyramids stretched on the rim of the cylinder. The heights of the rollers are much smaller than the upper part of the object.

Activity objectives

The creation of a three-dimensional digital Tubiteykas collection was carried out during the Virtual Scientific Expedition of the Lublin University of Technology to Central Asia in May 2021 in the COVID-19 period [14]. The organisation of the virtual expedition had several practical goals to achieve.

- Conducting remote training of employees from Samarkand State University scanner that was delivered to them.
- Performing, under the supervision of employees from Laboratory of Intelligent Systems Programming and Computer 3D Technology (“Lab 3D”) of Lublin University of Technology (communication via the Zoom platform), 3D scanning of ceramic objects and the so-called soft objects (made of fabrics) by people located in Samarkand.
- Post-processing of the data obtained by employees from “Lab 3D” after sending them to Poland.
- Creating a tubiteyka collection and (SamSU) in the use of the 3D
- Placing it on the 3 Digital Silk Road portal (silkroad3D.com).

Performing scanning and processing of acquired data

Training stage

The subject of 3D scanning was a collection of tubiteykas – Uzbek headgear, both male and female, from the 1960s and 1970s. Due to the fact that tubiteykas are most often made of easily deformed material, it was decided to scan only the outer surface. When inverting the tubiteyka, its shape would change, which would make

it impossible to combine scans of the interior and exterior. The inner side, as not having any decorations, was considered irrelevant.

An unforeseen circumstance disrupting the implementation of the tubiteyka scanning task was the COVID-19 pandemic, which prevented the arrival of the scanning team on the scheduled date. The necessity to carry out the project's tasks despite these adversities forced the use of an alternative plan. It was decided to implement the scanning process itself by the project partners staying in Samarkand, Uzbekistan. For this purpose, the scanning set consisting of the Range Vision Neo scanner operating in the automatic scanning mode with a rotary table (12 partial scans per full scan) was transported to the employees of SamSU. The Samarkand partners had their own desktop computer (I7 processor, 8 GB RAM with N-Vidia graphics card), which was sufficient to operate the device. The second, identical set was at the disposal of the employees of "Lab 3D" in the LUT. In order to enable the implementation of the 3D scanning process by the project participants representing SamSU, who did not have experts in this field, it was necessary to conduct on-line training. Such training was carried out with the use of the Zoom platform allowing remote access to the computer and software located in Samarkand (Fig. 5.33).

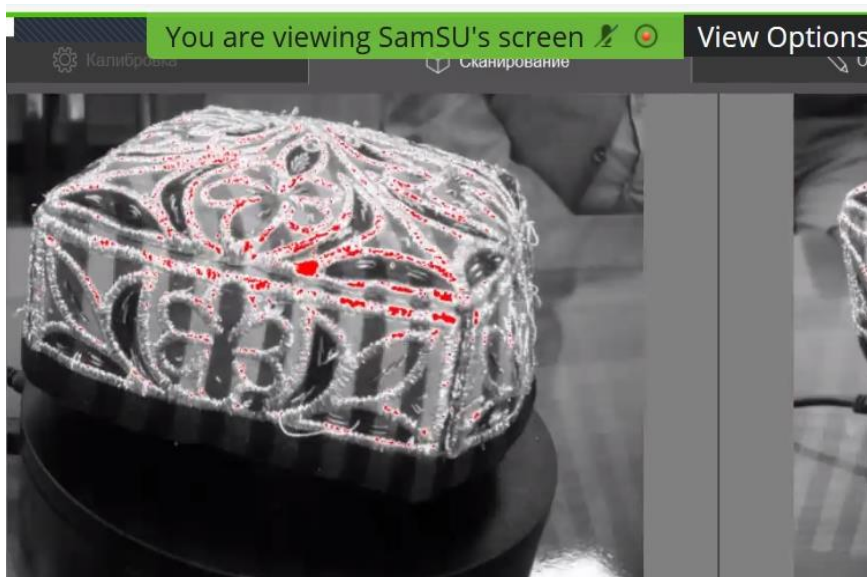


Fig. 5.33. Screenshot of the scanning process during on-line training, with remote control of the computer in SamSU by a person from "Lab 3D". By the authors

The following values were considered to be the optimal set of scanning process parameters for this type of task: scanning distance 22 cm, which gave a data acquisition area of 20 cm in diameter. Scan mode is selected in a room with uniform lighting. After placing the tubiteyka on the turntable, the rest of the procedure is automatic, without the need to touch it, which could change its original shape. Depending on the colour, texture and decorations of the tubiteyka, 1 to 2 full scans were made.

The organised on-line training lasted 2 days (2 sessions, 5 hours each). A certain inconvenience of conducting the classes was the time difference between Lublin and Samarkanda, amounting to 3 hours. As a result, two people representing the SamSU University fully acquired the skills of preparing the scanner for its correct operation, i.e. starting the program, connecting the scanner and turntable, calibrating the scanner, setting the appropriate parameter values and the implementation of 3D scanning with the use of a rotary table. During the course, it turned out to be helpful that both teams – the training and the trainee had their own copies of the scanning set.

3D scanning stage

The actual process of scanning a set consisting of 21 tubiteykas was preceded by sending photos of the hats prepared by the Samarkand side, so that LUT employees could choose the right parameter values for objects that differed primarily in terms of colour, surface texture and decoration. The process was carried out under the remote supervision of experts from the LUT (Fig. 5.34).

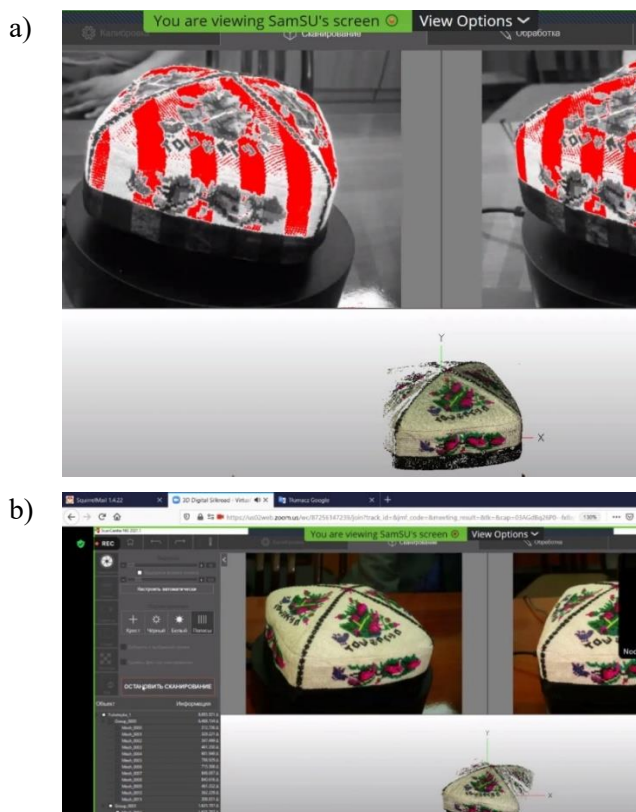


Fig. 5.34. Different phases of the 3D scanning process of an object: (a) visible fringes projected onto the original object, (b) preview of the original object lying on a turntable. In the lower part of both pictures one can see the state of digital representation of the object with automatic appending of current data. By the authors

Tubiteyka scanning was carried out in three sessions done within one week. Each session lasted about 5 hours. The first session was dedicated to testing the correct settings of the scanner parameters. The main problems during scanning were the correct setting of the sensitivity of the scanner cameras depending on the colour of the tubiteyka's cover. The possibility of remote consultations with LUT experts during the execution of the scan was very helpful here. During its duration, it was possible to digitise the first three tubiteykas. The next two sessions were used to make scans of the remaining objects. The collected raw data (36 GB) was then sent by employees from SamSU to the LUT partner where they were further processed.

Data processing stage

The obtained data were subjected to preliminary analysis, as a result of which 12 tubiteykas were selected for further processing and creation of their digital 3D models. The process of building the 3D base model was carried out in the software dedicated to the RangeVision ScanCenter scanner (Fig. 5.35).

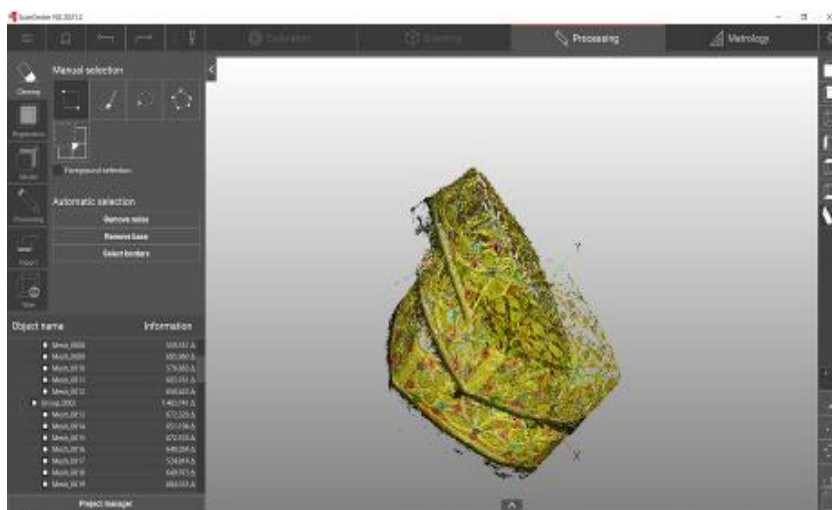


Fig. 5.35. Process scans in RangeVision ScanCenter. By the authors

The processing of a single tubiteyka took about 7 hours, which was many times the time spent on data acquisition (i.e. about 30 minutes). Most of the time was spent aligning the partial scans with each other and generating one complete digital 3D object from them. These activities led to the generation of the so-called digital base 3D models, which were characterised by high quality, but also significant file sizes averaging around 150 MB. In the second stage of processing, due to the decision made to disseminate the caps obtained in the 3D scanning process and creating a virtual collection, conversions of the digital base 3D models to simplified models were performed. “Lean” models were generated, suitable for presentation on portals available on the Internet.

The results

As a result of the performed work, 12 digital base 3D models were obtained with an average complexity of the surface represented by a mesh of about 500,000 triangles and a texture with a resolution of 4096x4096 pixels (Fig. 5.36).



Fig. 5.36. An example of the obtained digital 3D base model of a tubiteyka. By the authors

The 3D models generated for publishing on the Internet were characterised by the reflection of the surface, on average by meshes with a size of about 250,000 triangles, so their total size was nearly two times smaller. The collection of digital 3D models of the tubiteyka has been made available on the four-language web portal 3D Digital Silk Road (silkroad3D.com) (Fig. 5.37). 3D models of tubiteykas, for better presentation, were placed on an artificial head. They can be enlarged or reduced and freely rotated using the mouse.

Discussion

The use of the values of the parameters of the 3D scanning process of tubes adjusted to their different colours and textures resulted in the improvement of the quality of the obtained data.

The reduction of the number of triangles reflecting the tubiteyka's surfaces did not affect the quality of the displayed 3D model, especially when it concerned mobile devices whose screens do not exceed the size of six inches.

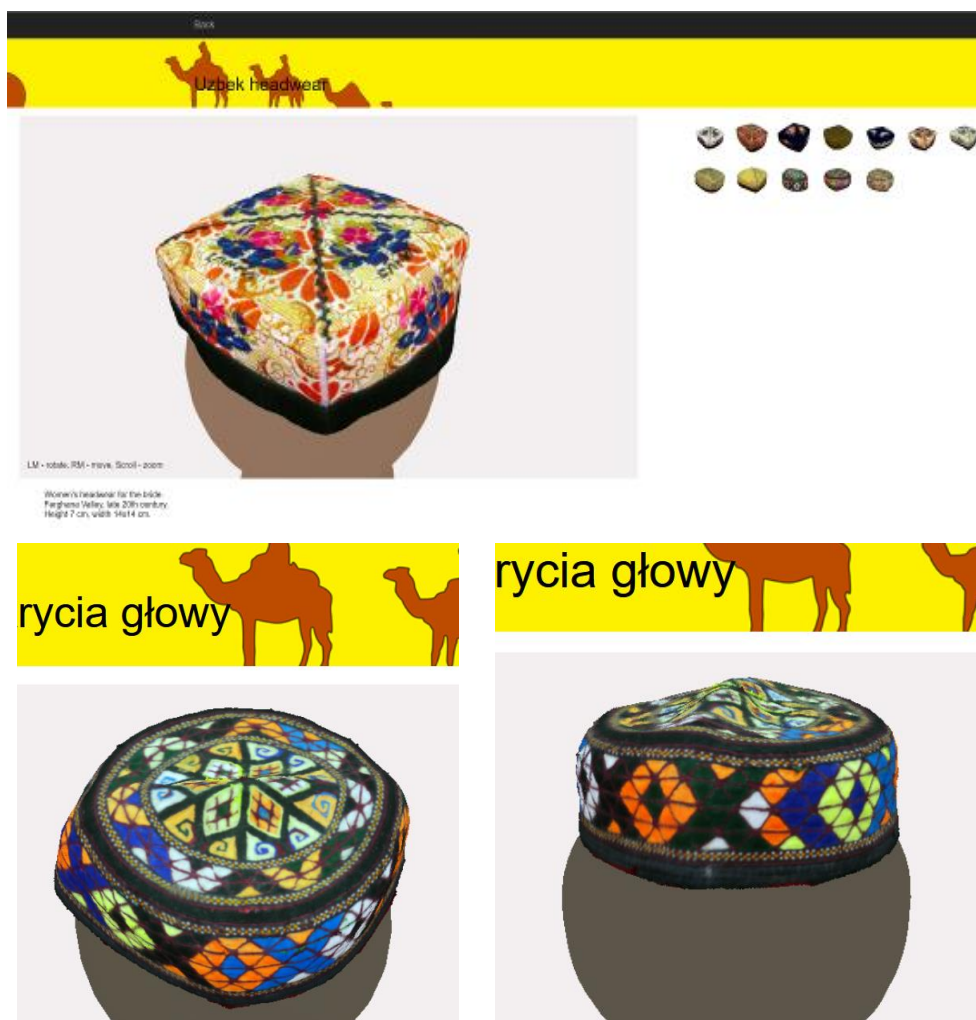


Fig. 5.37. Virtual tubiteyka exhibition available on silkroad3d.com. By the authors

Conclusions

The on-line training of the 3D scanning process brought the expected results, as evidenced by the performance of 21 tubiteyka scans.

The use of digitisation with the use of a 3D scanner working in the technology of structured light has brought the expected results. The obtained data allowed, in most cases, to generate complete digital 3D models of tubiteykas.

The process of 3D scanning of objects made of fabrics of various colours, textures and decorations is not an easy and simple issue, as evidenced by the fact that about 40% of data acquisition attempts were not of good quality.

5.6. Sher-Dor Madrasah mosaic

Sher-Dor Madrasah in Samarkand and the mosaic on its front portal

The Sher-Dor Madrasah (Uzbek for “tiger-owning”) in Samarkand is part of the Registan Ensemble. It was established in the years 1619–1636 as the second one after the Ulugh Beg Madrasah. On the set of the Registan Ensemble (Fig. 5.1), the Sher-Dor Madrasah is marked with number 2.

The mosaic decorating its pediment depicts tigers (or lions, actually a fantasy animal: a tiger with a lion’s mane) hunting a doe against the backdrop of sunny faces (Fig 5.38). This mosaic is a showcase of Samarkand and one of the main reasons why tourists visit Registan. It is also one of the symbols of Uzbekistan – it is depicted on the 200 UZS banknote and coin. The Sher-Dor Madrasah image is also on the new 5,000 UZS banknote.

As a result of neglect and earthquakes, the madrasah building was badly damaged at the beginning of the 20th century. The mosaic on its pediment was severely damaged (Fig. 5.39). The mosaic was restored (or actually re-made from scratch) in 1962, keeping the old technology. It consists in cutting out irregular glazed tiles and fixing them on gypsum boards.

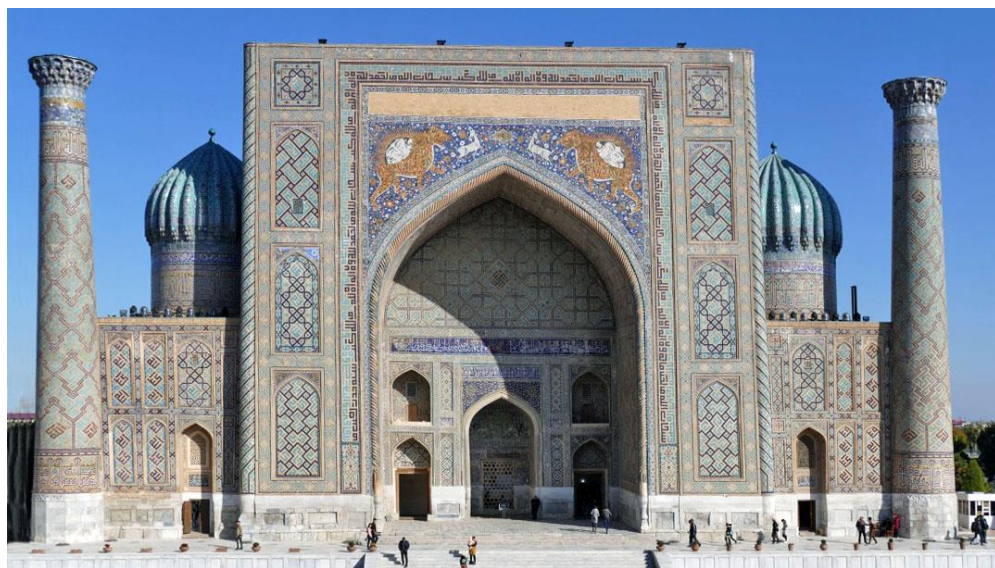


Fig. 5.38. Contemporary Appearance of the Sher-Dor Madrasah. By the authors



Fig. 5.39. State of the Sher-Dor Madrasah at the beginning of the 20th century. By <https://www.loc.gov/pictures/collection/prok/item/2018680120/>

Objectives of activities

In 2018, during the Second Scientific Expedition of the Lublin University of Technology to Central Asia, a team of scientists from the University performed a scan of Registan Square, including the frontage of the Sher-Dor Madrasah. The purpose of the scanning was to archive the geometry and appearance of the Registan Ensemble buildings. It was planned to make panoramas of 360° and VR contents.

In connection with the planned reconstruction of the mosaic (by making it anew), the Director of the Registan Ensemble Museum asked for two works:

- making templates in a 1 : 1 scale of the mosaic appearance on the front of the madrasah in the form of files to be printed in colour,
- counting the area taken up by tiles in each of the colours of the mosaic.

Both tasks were not trivial.

The templates had to be made with a fairly high accuracy (in the order of millimeters), which, with an area of over 100 m², is not an easy task. Similarly, counting the area of irregularly shaped tiles in certain colours.

The needs of the museum resulted mainly from the condition of the mosaic, which was repaired with gypsum (sometimes painted with oil paint) and secured with a metal mesh. With the help of bolts (Fig. 5.40), the mesh was installed to protect tourists from the plates falling off from a great height.

Due to the mesh (but also the inability to close or even cover the object for tourist traffic), the conservators could not make the templates using the traditional method, i.e. by tracing the mosaic geometry with tracing paper and pencil.

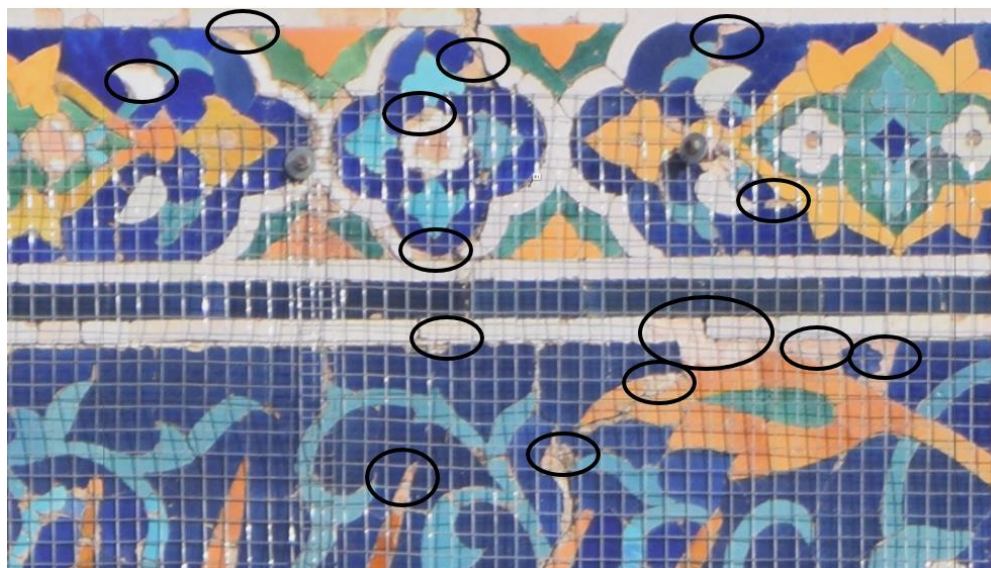


Fig. 5.40. The mesh securing the mosaic, its fastening elements and missing tiles, supplemented with gypsum (marked). By the authors

Methodology and implementation of works

To achieve the set goals, the mosaic was scanned with a Faro X330 3D laser scanner with an accuracy of approx. 1 mm. The scanner has a built-in digital camera, but its resolution is too low for such a large object and the development of a template in a 1 : 1 scale with the required accuracy. Therefore, it was decided to combine the TLS method and photogrammetry. A 3D scan of the madrasah's frontage was made in 2018. During the 3rd Scientific Expedition of the Lublin University of Technology to Central Asia in 2019, a series of high-resolution digital photos were taken, including fragments covering the entire mosaic. For this purpose, a Nikon D 5300 camera was used, equipped with a Nikkor lens with a focal length of 18–140 working with a resolution of 6000x4000 pixels (24 Mp).

The image obtained from the scanner, despite its low quality, made it possible to determine characteristic points on objects, necessary in the photogrammetry method to superimpose images from digital photos on a 3D mosaic model. As a result, a file containing the mosaic image was produced with high accuracy.

There was a need to verify the results with reality. For this purpose, selected image fragments were sent to Samarkand to check the accuracy of the mapping on site (Fig. 5.41).

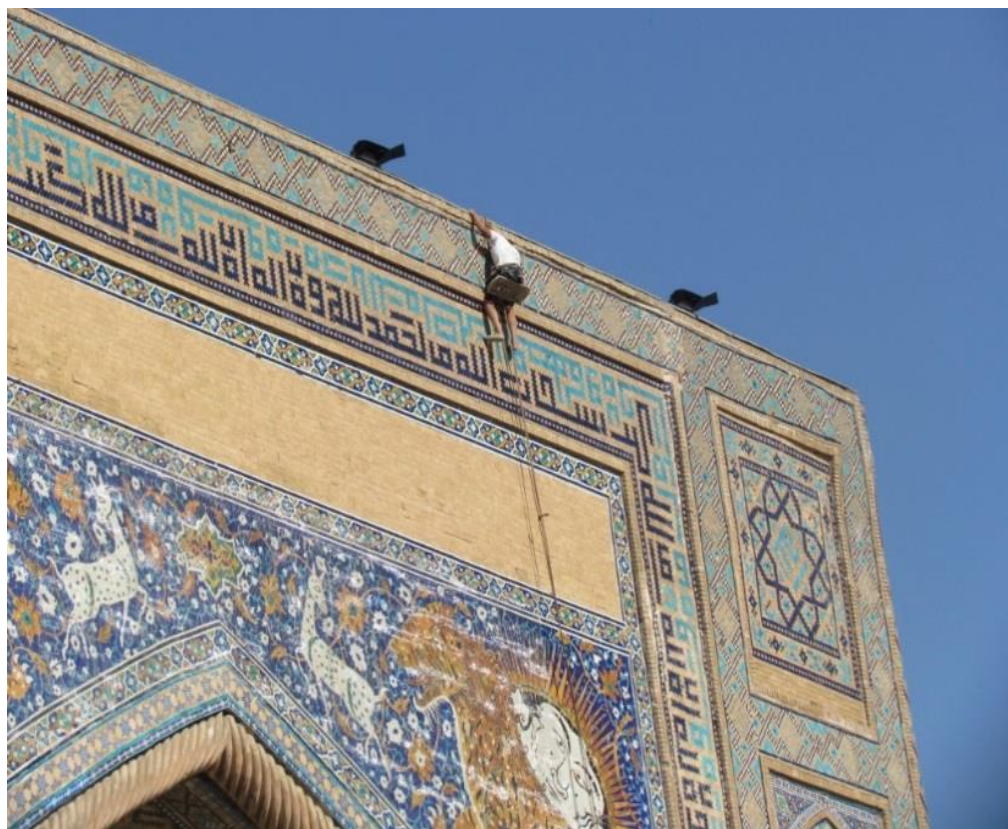


Fig. 5.41. “Mountain climber” working on the front of the Sher-Dor Madrasah (illustrative photo).
By the authors

After positive verification, it was possible to proceed to the next task, i.e. to determine the surface of each colour of the tiles on the mosaic. The workflow shown in Fig. 5.41 was used. One of its elements is the colour classification algorithm [15], developed by the authors (task “Clasification of pixel colours from the ROI for a fragment” in Fig. 5.42). The C++ language and `bitmap_image.hpp` library were used in the implementation of the algorithm. Listing 1 shows the implementation of the colour classification algorithm.

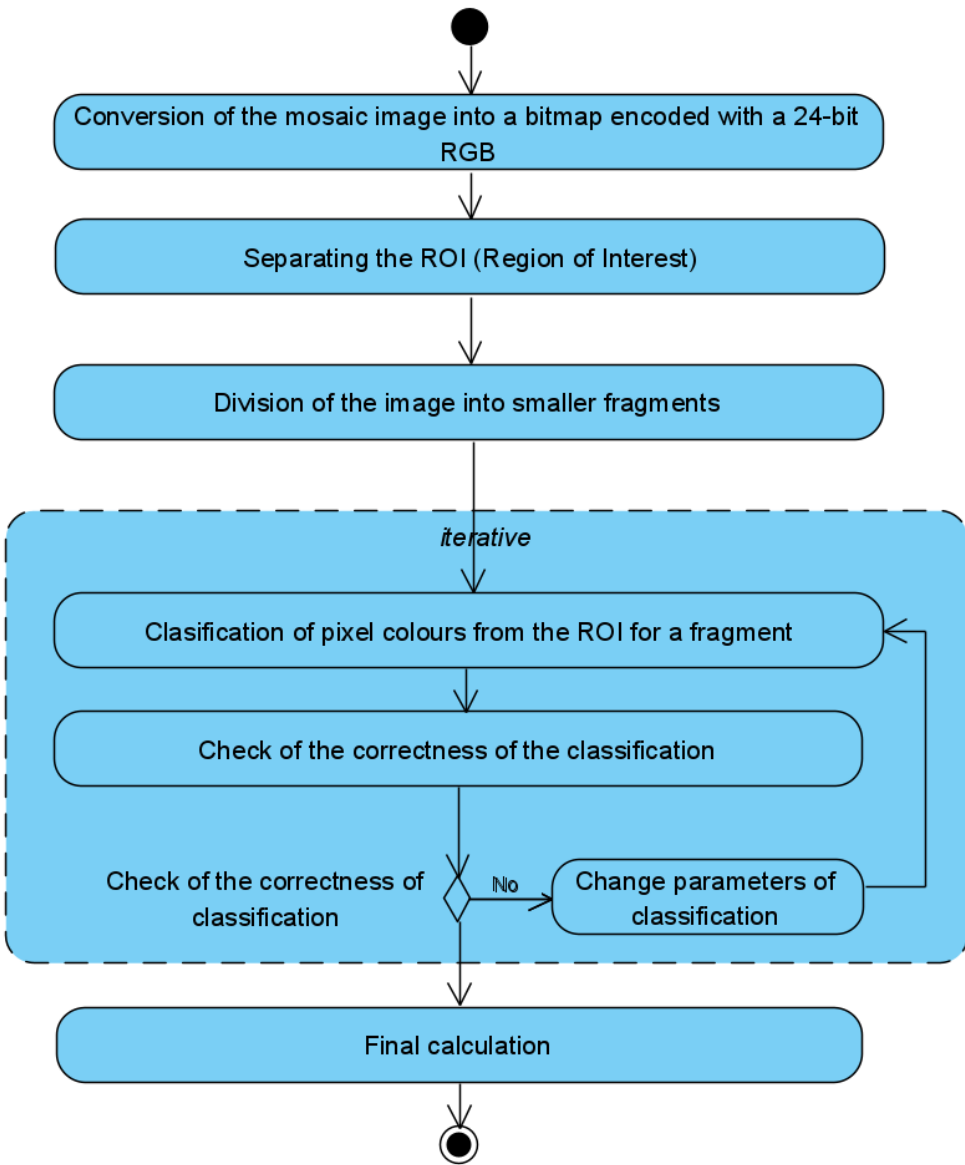


Fig. 5.42. Tile area calculation workflow in each of the mosaic colours. By the authors


```

vector<int> classification_total(vector<rgb_t> K,vector<float> E,bitmap_image image , int* L, int*TP, int*CP )
//zwraca wektor z liczbą zaklasyfikowanych punktów do K oraz info *L o liczbie punktów zaklasyfikowanych wielokrotnie
//oraz liczbę pixeli ogolem *TPi liczbę sklasyfikowanych pixeli *CP
{
    vector<int> NN(N);//liczba pikseli w danym kolorze
    fill(NN.begin(),NN.end(),0);
    unsigned int total_number_of_pixels = 0;

    const unsigned int height = image.height();
    const unsigned int width = image.width();
    int p=image.pixel_count();

int i,l=0,redpoint=0;
for (std::size_t y = 0; y < height; ++y)
{
    for (std::size_t x = 0; x < width; ++x)
    {
        rgb_t point=image.get_pixel(x, y);

        if(point.red==255 && point.blue==0 && point.green==0)
        {redpoint++;
        }
        else
        {//klasyfikacja bez czerwonych
        classification(K,E,point, &i, &l );

        if(l==0)image.set_pixel(x,y,255,0,0);//niesklasyfikowane kolory zamienia na czerwone
        if(l>0) {
            NN[i]++;

            image.set_pixel(x,y,K[i].red,K[i].green,K[i].blue);//zamiana kolorow
            // image.set_pixel(x,y,0,0,0);//sklasyfikowane kolory zamienia na czarny
        }
        if(l>1) *L=*L+(1-l);
        //*L=1;
        }
    }
}
}

```

Listing 1. Listing of the pixel colour classification function ROI of the mosaic image. By the authors

The results

TSL scanning of the Sher-Dor Madrasah frontage provided data on the geometry and appearance of the site. On the basis of the obtained data, basic 3D models of the pediment were developed and used to develop panoramas of Registan Square and VR contents.

As a result of the TSL scanning work and the use of the photogrammetry method, a digital image of the fronton mosaic with a size of 2.9 GB was created, which is the basis for further work. This image has a resolution of approx. 50 dpi (i.e. approx. 2 pixels per 1 mm horizontally and vertically) over an area of over 100 m².

In order to be able to print templates in 1 : 1 scale, 51 files were generated containing mosaic templates with dimensions of 1x3 meters each. Images on files were extracted and converted to .pdf format. The files were used to print the templates on printers intended for printing advertising banners (Fig. 5.43). Problems with maintaining the correct representation on the printouts were solved by the company

printing the templates. 51 partial templates were printed, which were then physically combined into one template for presentation. It is planned to recreate the mosaic on the ground using 1x3 meter templates.



Fig. 5.43. Printed templates at Registan Square. By the authors

The mosaic image file was converted from the original .psb format to .bpm format with 24b colour coding in the RGB palette divided into four files (it was related to the quantitative limitations of the software used). The ROI (Region of Interest) (Fig. 5.44) – was manually determined on it by making the non-ROI pixels red, i.e. (255, 0, 0). For the .bpm file, the colour classification algorithm of each pixel was used. The classification is carried out with the assumed accuracy (error) using the algorithm described in [15] and presented in Listing 6.1. The accuracy was changed manually and the percentage of classified and double-classified pixel colours was controlled. The classification process was carried out on a computer with Intel Core i5-8250U, 1.60 GHz, RAM 8 GB, 256 GB SSD running under 64-bit Windows 10. The average computation time for one (out of four) files was 7.5 minutes on average.



Fig. 5.44. Analysed Mosaic Area (ROI). By the authors

As a result of work on determining the surface area of ceramic tiles in each of the colours, the results presented in Table 5.2 were obtained. The calculations took into account the ROI surface area for the mosaic, i.e. about 103.4 m². The number of pixels in colours was clearly classified from over 70% of the ROI of the mosaic image, with the number of pixels in the ROI being over 500 million. The remaining elements of the picture are the mesh, elements of its assembly, tile joints, gaps and repairs after missing tiles. The percentage of multiple classified colours of points was about 2%. The classified number of points in specific colours allowed to estimate the surface area of the tiles in each of the colours.

The obtained accuracy of colour classification (over 70%) is sufficient to formulate an order for tiles in each of the colours (due to the practice of ordering 20–30% more of them).

Table 5.2. Results of the determination of ceramic tile colours surface areas on the Sher-Dor Madrasah mosaic in Samarkand

Colour	R	G	B	% of area	Aera, m ²
blue	120	190	22	11.806%	12.207
navy blue	10	10	220	23.506%	24.305
white	220	220	220	20.019%	20.700
black	40	40	40	7.463%	7.717
light brown	240	200	140	23.107%	23.893
brown	220	120	70	11.039%	11.414
green	94	145	120	3.017%	3.119
light pink	240	180	166	0.044%	0.046
			Total:	100.000%	103.389

Discussion and conclusions

The tested mosaic is huge – it has an area of over 100 m². It is difficult to access (min. 15 m above ground level and constant tourist traffic) and difficult to copy using traditional methods (due to the metal mesh fixed in front of it). The proposed methods made it possible to obtain its dimensions and image for further use.

Thanks to the combination of TLS and photogrammetry techniques, the task of developing mosaic patterns on a scale of 1: 1 was fully completed. The comparison of computer models of the mosaic geometry appearance with reality (carried out using the in-situ method) indicates a very high accuracy of mapping the geometry of the mosaic tiles on a very large surface.

The task determination of ceramic tile colours surface areas on the medieval Sher-Dor Madrasah mosaic was successfully completed, despite many significant distortions in the colour of the mosaic. The developed and implemented algorithms, despite numerous distortions of the mosaic’s appearance, allowed for automatic colour classification of over 70% of the mosaic surface. The achieved result allowed to estimate the number of ceramic tiles in each of the given colours that must be ordered in order to renovate the mosaic.

5.7. Afrasiab virtual museum

Afrasiab Museum in Samarkand

Afrasiab is an ancient trading city that was located on the Silk Road. It was established around the 5th century BC and developed very dynamically, being a well-known place for the exchange of goods and services, as evidenced by the vastness of the area it occupied – nearly 200 ha. The end of the city’s development and its complete destruction occurred in 1220, when it was plundered and destroyed

by the Genghis Khan invasion [16]. Currently, the area occupied by the ancient city is the area of archaeological excavations within the administrative area of Samarkand (Fig. 5.45).

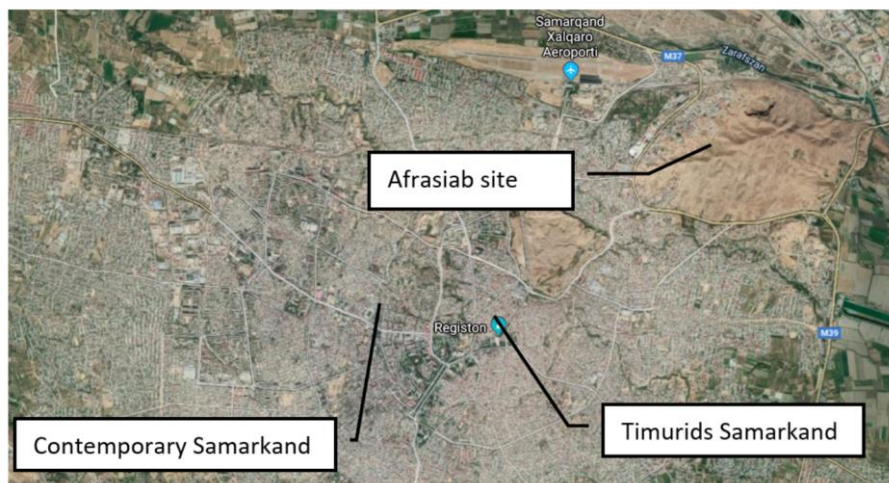


Fig. 5.45. The ruins of the city of Afrasiab next to modern Samarkand in Uzbekistan. By Google

The Afrasiab museum, founded in the late 1960s and early 1970s, is located on the excavation site and contains over 20,000 exhibits (glazed potters, plates and dishes, pitchers, coins, swords, knives, glassware, remnants of residential and public buildings (baths) from the site excavations of the city (Fig. 5.46). A unique artefact unearthed among the ruins of the city are the famous frescoes called the Ambassadors' Painting or the Hall of Ambassadors murals [17].



Fig. 5.46. View of the pediment of the Afrasiab Museum building designed by Armenian architect Bagdasar Arzumian in 1970. By the authors

Objectives of activities

In 2017, during the First Scientific Expedition of the Lublin University of Technology to Central Asia, a team of scientists associated with “Lab 3D” (Laboratory of Intelligent System Programming and Computer 3D Technology) performed 3D digitisation of several dozen artefacts from a city that no longer exists, and kept in the Afrasiab museum [18]. Two 3D scanners working in structured light technology were used for this work: Artec Spider and Artec Eva, which were presented in detail in Chapter 2. In 2019, during the presence in Samarkand (the Third Scientific Expedition of the Lublin University of Technology to Central Asia) the same team performed the 3D digitisation of the famous frescoes of the “Hall of Ambassadors murals”. This time the FARO Focus X 330 laser scanner was used (more information in Chapter 2).

The original goal of the activities from 2017, after appropriate processing of the collected data, was to prepare a collection of digital 3D models that were made available on the “3D Digital Silk Road” portal (silkroad3d.com). The data collected in 2019 were used to prepare an omnidirectional panorama of the room in which unique frescoes are presented. The prepared digital panoramas differed significantly from what the visitors are used to, as the four pillars supporting the ceiling were removed. So the frescoes in the digital version are not obscured by anything.

The times of the Covid period meant that the possibilities for tourists to travel and visit cultural heritage sites were significantly limited. Hence the research goals. Preparation of a virtual and interactive exhibition with 3D models of ceramic artefacts and a throne room with frescoes found on the Afrasiab archeological site using Virtual Reality (VR) technology for popular smartphones. In addition, the development of an application that allows to record the course of virtual walks, in the form of the so-called heat maps.

Implementation of the application “Acient Afrasiyab”

The application called “Acient Afrasiyab”, which was implemented in the concept of Virtual and Interactive Exhibition (VIE), presents selected exhibits from the Afrasiab museum in Samarkand. The application allows visitors to move freely in an artificial 3D virtual world and interact with digital 3D objects that have been placed in it. The innovative features of the application are: application architecture that allows the display to be changed through data exchange, the ability to register the visitor’s path through the exhibition and the use of open source tools [19].

Virtual and Interactive Exhibition are characterised by many advantages: high accessibility due to the use of a smartphone, low cost of preparation and sharing, no limit to the number of visitors – everyone can download applications, visiting comfort, no need to travel to the selected place, and accessibility for disabled people. Exhibitions prepared in real museums generate many restrictions for visitors: opening hours of the museum, inability to approach the exhibit, inability to see objects from all sides (showcases by the wall).

Objects placed in the virtual realm were obtained in the process of 3D scanning of objects made available by the management of the museum (Figs. 5.47 and 5.48).

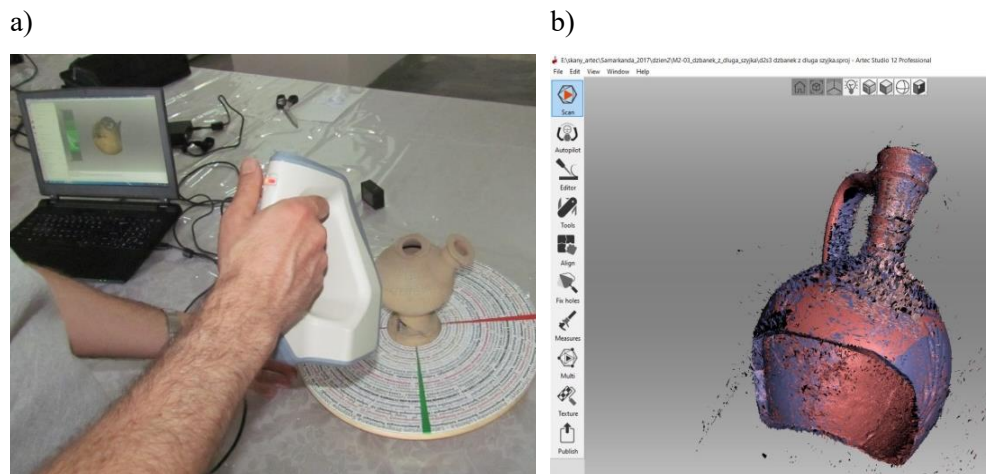


Fig. 5.47. Creation of digital 3D models: (a) 3D scanning of a ceramic vessel using the Artec Spider scanner, (b) processing of acquired data. By the authors.

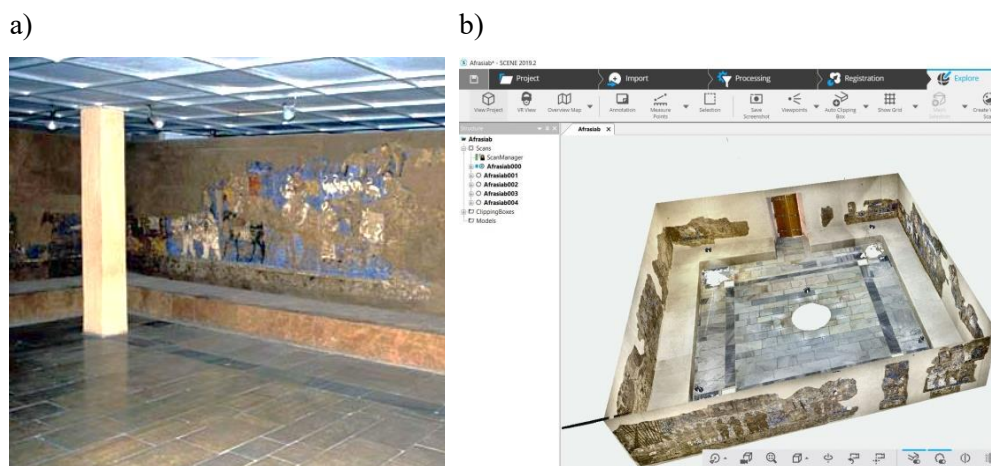


Fig. 5.48. The Hall of Ambassadors in Afrasiab city: (a) view with pillars, (b) 3D model after assembling from scans obtained from the FARO Focus X330 scanner. By the authors

In the developed application “Ancient Afrasiyab”, the proprietary VIE concept was used, combining the feeling of immersion with the presentation of real 3D models. The whole was oriented primarily to the presentation of exhibits, which combines the features of the presentation of the environment (exposure) in a manner known from 3D games (first-person perspective) with immersion in this environment

using VR technology. The developed application is based on generally available VR technical kits using a smartphone device, which is currently the basic computer that most of the population has, regardless of age or education. For this type of device, there are free drivers as well as cheap accessories and glasses for viewing images in the VR version. The technical requirements necessary to run the prepared “Ancient Afrasiyab” application are as follows: screen at least 4.5 inches, resolution not less than full HD, magnetometer, graphics system supporting 3D graphics rendering.

The preparation of the “Ancient Afrasiyab” exhibition from the technological point of view was divided into two stages: preparation of the objects and construction of rooms for the exhibition being created and the creation of a framework for VR applications that allows the creation of VIEs.

The preparation of the skeleton of the application included the implementation of the VIE application in the 3D graphics engine. IT specialists mainly take part in the process of creating the framework of the VIE application, and the role of museologists is limited to proposing new functions or reporting bugs. The skeleton construction process was carried out according to the following scheme (Fig. 5.49).

Phase 1 (Fig. 5.49) is related to the selection of appropriate technologies for the preparation of the application. Phase 2 concerns the construction of individual functionalities of the application. Phase 3 includes combining the functionality into the framework of the entire application with the use of 3D test objects and background elements of the exhibition halls. The application skeleton design consisted of a graphic and programming part. The Unity environment was used to prepare the virtual scene and embed the scripts that control and define the way of rendering the image. The Visual Studio development environment was used to implement core programming functions, scripts and data models.

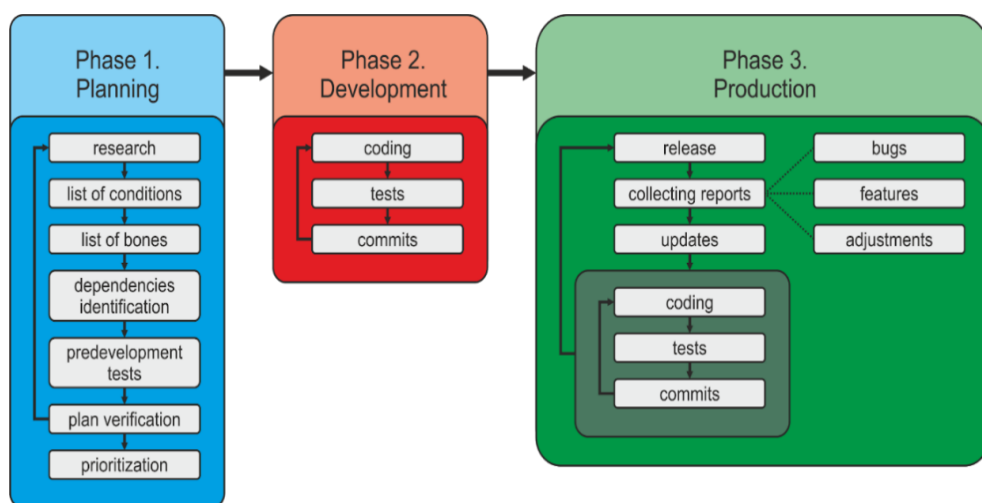


Fig. 5.49. General schema of Virtual & Interactive Exposition realisation. By the authors

Due to the need to shorten the waiting time for downloading 3D models to the virtual tour environment, the triangle meshes describing the surfaces of 3D models were simplified and the resolution of textures for mapping them was reduced. Thanks to these actions, the size of the files was reduced by several dozen percent without any visible deterioration of their visual quality (Figs. 5.50–5.52). This was enough for the images downloaded to personal mobile devices to be performed on an ongoing basis with the expected frequency of at least 30 frames/s.

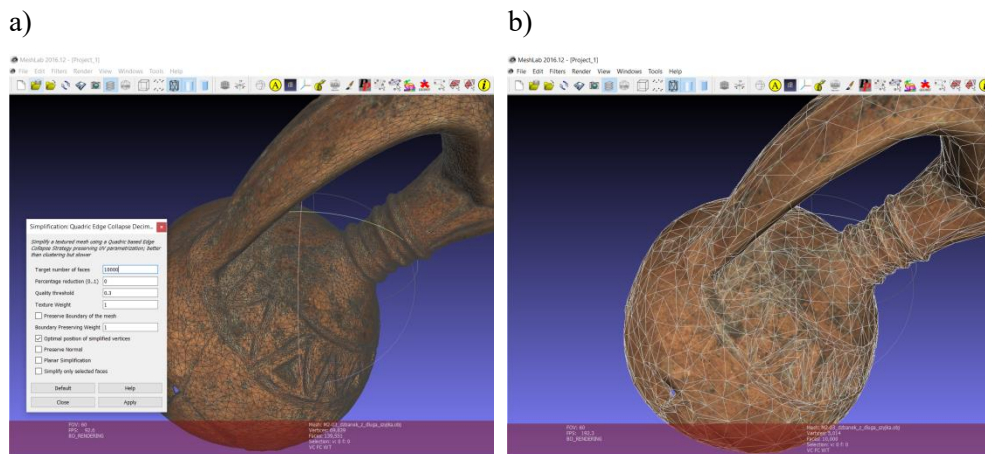


Fig. 5.50. Jug mesh reduction: (a) original size, (b) minimised. By the authors

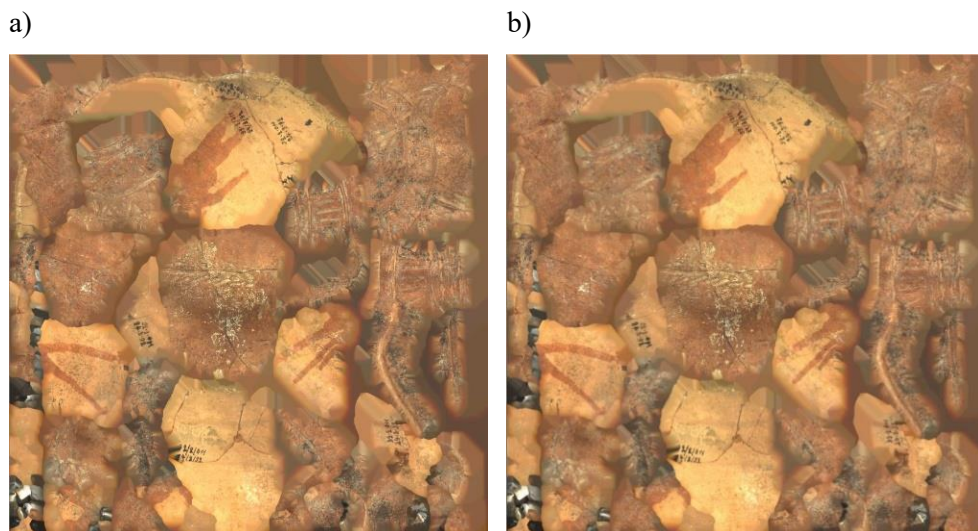


Fig. 5.51. Decreasing the detail of the jug texture: (a) original size, (b) minimised. By the authors

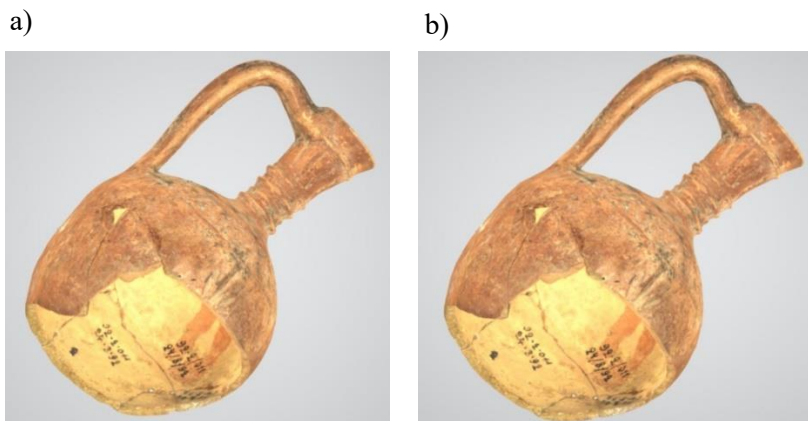


Fig. 5.52. Comparison of the quality of the jug view: (a) before reduction, (b) after reduction.
By the authors

The construction of a virtual stage for the “Ancient Afrasiyab” application prepared in the Unity graphical environment required embedding the sources of the world, additional collision limiters and a virtual avatar control module combined with stereoscopic projection on VR glasses (Fig. 5.53).

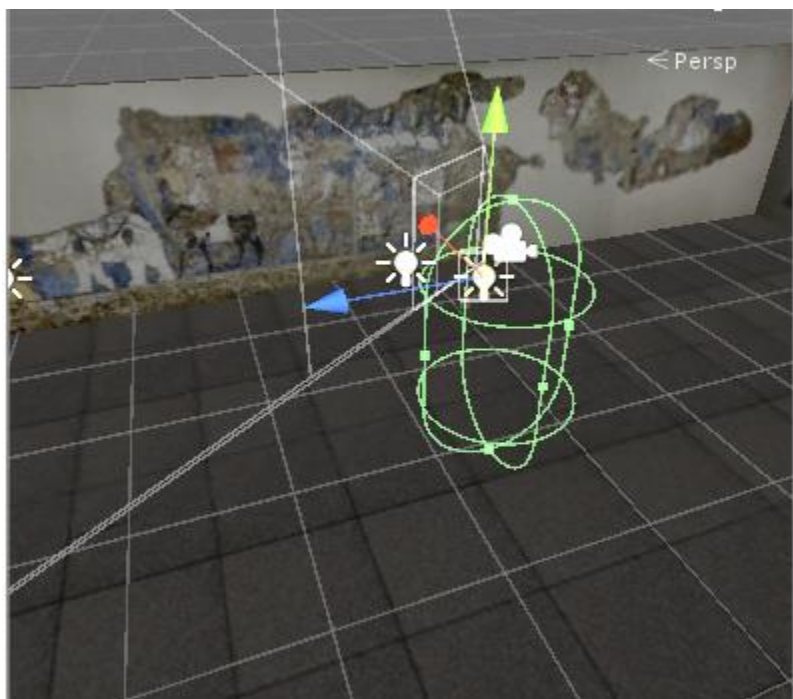


Fig. 5.53. Preview of the test scene from the TPP (Third Person Perspective) perspective. By the authors

Results

In the “Ancient Afrasiyab” application, 12 3D models of exhibits selected by the employees of the Afrasiab Museum, located in four virtual rooms, were made available (pilot version). The application implements the original VIE concept based on VR technology. The 3D models have been appropriately simplified and adapted to the requirements of the VR presentation realised with the use of a Smartphone. The exhibits (objects of small sizes were proportionally enlarged) were placed on pedestals, to which there was free access from all sides (Fig. 5.54). Visitors, thanks to the creation of the phenomenon of immersion in VR, can approach the exhibits in any order, using simple forward or backward controls. Moreover, it has the ability to activate billboards containing text information about the object to which he approached (Fig. 5.55).



Fig. 5.54. Preview of the view from the application – a walk around the room with the exhibits.
By the authors

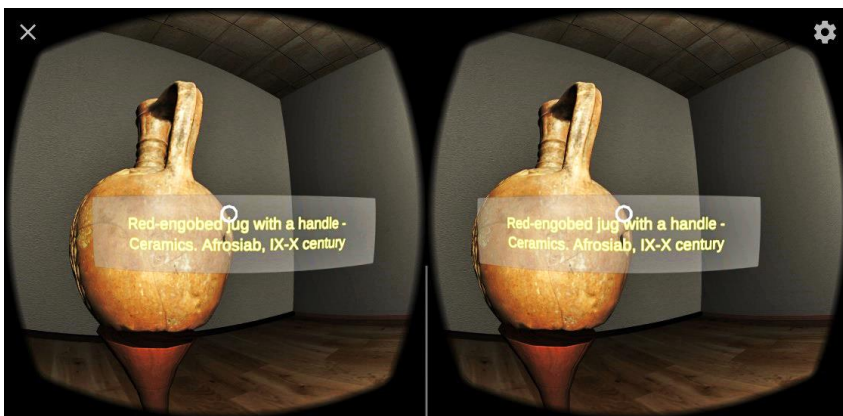


Fig. 5.55. Stereoscopic view of the object with the description displayed from the perspective of the application running on the target device. By the authors

The last room of the VIE exhibition “Ancient Afrasiyab” contains a representation of the room with a presentation of the Ambassadors’ Painting wall frescoes in real sizes (Fig. 5.56).



Fig. 5.56. Preview of the view of the virtual scene with frescoes with the 4. columns supporting the ceiling of the Hall removed. By the authors

The application “Ancient Afrasiyab” was tested in 2019 during the scientific seminar “3D Technology in Cultural Heritage” at the Kyrgyz State Technical University in Bishkek (Kyrgyzstan) (Fig. 5.57). At the outset, the respondents (students and university staff) were instructed on how to move around the rooms and how to interact with the exhibits on display. Participants could freely move around all rooms and view the prepared exhibits without an imposed scenario. The end of the research session was to put away the VR glasses.

The prepared software made it possible to save data on the route of each virtual walk (duration of the walk, viewing individual objects, order of visiting, etc.). The final effect of the collected data was the generation of a heat map representing the traveled route and the time spent by a single participant in the rooms and with specific museum artifacts (Fig. 5.58). The red colour means longer time of viewing objects by visitors to the exhibition.



Fig. 5.57. Pilot study of the application “Ancient Afrasiyab” at Kyrgyz State Technical University, Bishkek, Kyrgyzstan. By the authors

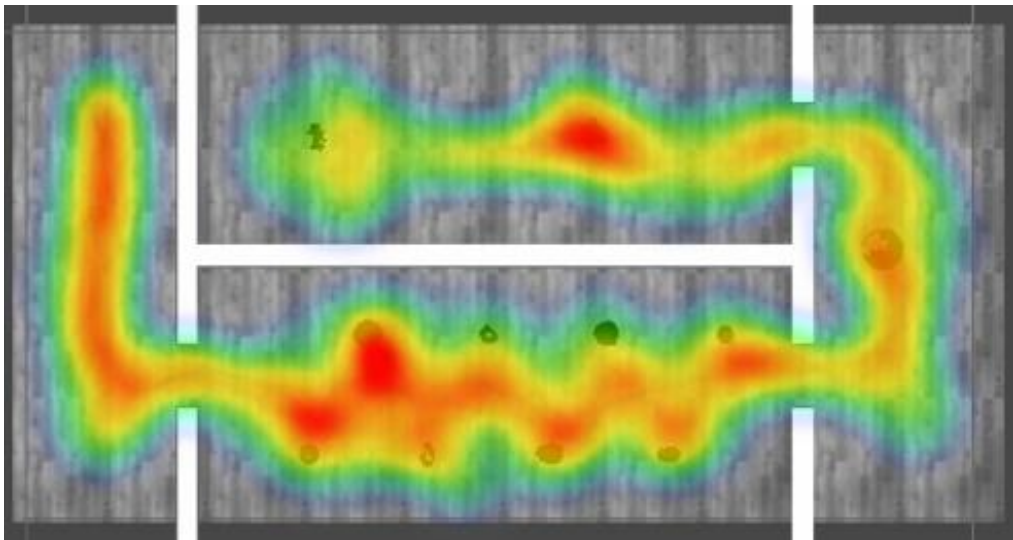


Fig. 5.58. Heat map of a virtual tour of respondents. By the authors

Discussion

The participants of the research pointed, first of all, to the fact that the presented billboards displayed after interaction with the viewed object should contain texts prepared in different languages. The Polish, Russian, Latin and English versions of the descriptions on the billboard after the interaction with the exhibit are shown in Fig. 5.59.



Fig. 5.59. Preview of the view from the application after modification. By the authors

Conclusions

Prepared optimised digital 3D objects for the exposition “Aicient Afrasiyab” allowed the respondents to interact with objects in individual virtual exhibition halls.

The application of the modular structure of the application allows for a quick change of the objects of the presented exhibition and its surroundings. The number of rooms and the arrangement of artefacts in them can be easily modified, which makes it easier to expand the exhibition and adapt it to current needs.

The solution in which a part of the virtual scene can be modified on the basis of the available database of 3D digital objects and diagrams of their arrangement, arouses great interest among museum professionals. Building a new version of the exhibition (improved arrangement, lighting, modified order of objects) using the existing objects is a much faster and simpler process compared to the need to carry out adequate modifications in the physical space. The results of the tests so far, of the application developed in the concept of Virtual and Interactive Exhibition with the participation of users, are very promising. The respondents agreed that the use of VR technology for museology and disseminating knowledge about culture is a very promising idea and that they are interested in enriching the prepared prototype application.

5.8. The coronation costume of Emir of Bukhara

The coronation garment of the last Emir of Bukhara embroidered with gold thread

In the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve the coronation garment of the last Emir of Bukhara is stored (Fig. 5.60), consisting of: dressing gown, salla (turban), mahsi and kaushi (high and low shoes). All the elements of the outfit come from the end of the 19th century. The gown and shoes are embroidered with gold thread, and the turban is made of a light silk fabric, also locally richly decorated with embroidery (including gold thread).

a)



b)



Fig. 5.60. The coronation costume of the last Emir of Bukhara: (a) exhibition in a museum case, (b) its surface. By the authors

The Emirate of Bukhara has existed for over 130 years in the territory of modern Uzbekistan, Kazakhstan and Tajikistan, with its capital in Bukhara. It was liquidated by the Soviet Red Army in 1920, and the Emir (Fig. 5.61) emigrated to Afghanistan. The Emir took many things with him, but his coronation garment remained.



Fig. 5.61. Emir of Bukhara. By: S.M. Prokudin-Gorski (<http://loc.gov/pictures/resource/prokc.21887/>)

Objectives of activities

Extensive research in the literature showed [20] that there were no cases of 3D scanning of historical garments with the SLS technique, carried out in a methodical manner. At the same time, it should be noted that historical costumes are perishable artefacts. They are exposed to the influence of atmospheric factors (mainly oxygen and moisture), light, destructive biological factors, etc. Besides, they are highly exposed to various random threats, such as theft and fire.

3D scanning of artefacts usually requires access to the surface of the object from multiple sides. This access very often requires moving the object, i.e. placing it in a different position. Such approach is impossible for fabric clothes – the outfit will change its shape when changing position.

The clothes are quite sizeable and have a large number of small details, such as weave or embroidery. Such differentiation makes it difficult to select a 3D scanner and the scanning process itself.

During the 3rd Scientific Expedition of the Lublin University of Technology to Central Asia, steps were taken to:

- checking whether it is possible to correctly scan garments in 3D using SLS, including those with a large number of small details and partly made of shiny material,
- determination of material and time resources necessary to perform the scan,
- detection of unpredictable problems with scanning clothes,
- testing in practice the developed methodology of 3D scanning of clothes using SLS,
- development of basic models of artefacts included in the coronation costume of the last Emir of Bukhara,
- dissemination of three-dimensional images of elements of clothing on the Internet.

Methodology and implementation of works

The works include the use of the Artec Eva scanner powered from the mains, cooperating with a laptop. A specialised rotary table was used to scan the stiff kaushi (low shoes), which facilitates the scanning process.

The work was carried out in one day in the museum's exhibition hall closed to visitors, with very committed support from the museum staff. Its implementation is presented in Fig. 5.62.

The project of scanning the coronation outfit took place in an ad-hoc mode – the team received an invitation from the museum to act overnight. Therefore, initial activities in the project included rapid literature research to search for analogous activity cases (and methodologies) on the Internet and in scientific databases. Literature research did not provide information on similar activities in the world.

Everything from planning to scanning took place in the museum. After scanning, the work related to the processing of the acquired data was carried out in the LUT laboratory. The workflow used in the work is presented in Fig. 5.63.



Fig. 5.62. 3D scanning of the elements of the coronation costume of the last Emir of Bukhara.
By the authors

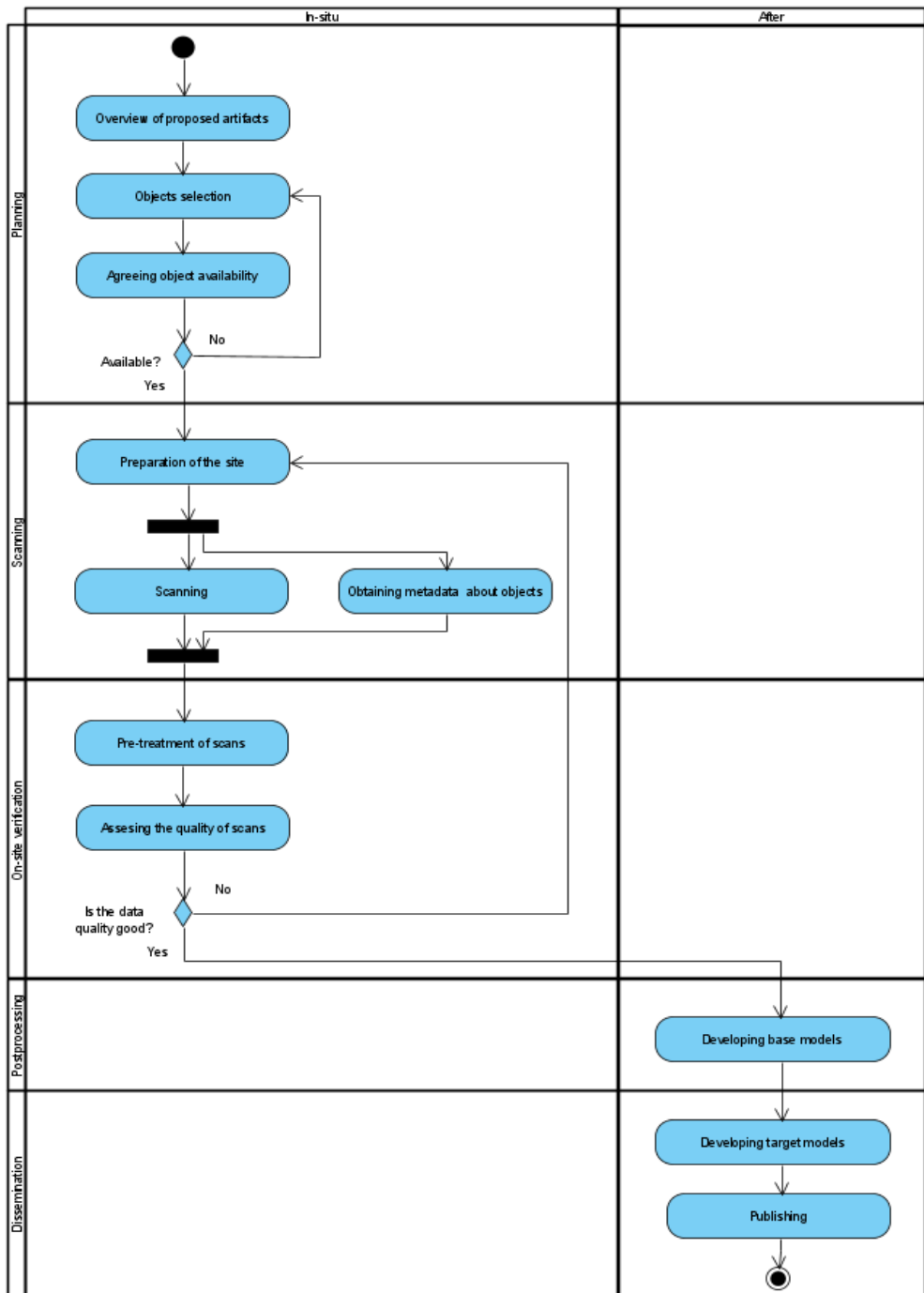


Fig. 5.63. Workflow for 3D scanning of elements of the coronation costume of the last Emir of Bukhara. By the authors

The in-situ activities were devoted to the review and selection of artefacts for 3D scanning (according to various criteria, including the availability of artefacts), the implementation of the scanning process and the initial control of its results. The set of the coronation costume of the last Emir of Bukhara was selected. Access to it was provided by museum staff.

During the scan, the artefacts had to be removed from the place of their presentation (i.e. from glass cases) and placed on improvised ad-hoc supporting elements: a dummy and/or a stand. Unfortunately, there was nothing in the museum to wrap a turban on and the head of one of the museum employees was used for this purpose (Fig. 5.64).



Fig. 5.64. Preparation of a turban for scanning by museum staff. By the authors

The works were performed with the use of:

- hand-held LSL Artec Eva,
- digital camera (Nikon D5300),
- laptop (processor i7, 32GB RAM, GTX 980 8MB graphics card),
- rotary scanning table (developed By the authors),
- software for work on site (Artec Studio 12 Professional),
- post-processing software (Blender v2.8, MeshLab v2020.04),
- ad-hoc supporting elements (dummy, tripod, table, etc.).

Electric extension cords turned out to be very important. In the museum, electrical sockets were placed very rarely and far away from the workplace.

The works were carried out by 3 members of the Lublin University of Technology team (IT specialists), supported by 4 employees of the museum. The total time of in-situ work was about 1.5 hours.

Results and their use

As a result of the work, 30 point clouds with a total volume of over 6 GB were obtained for 6 artefacts. Jet is an average of 5 clouds per object. The total number of measurement points acquired exceeded 146 million, with more than half (nearly 84 million, 3.5 GB) for the largest and most complex facility: the dressing gown.

In the post-processing procedure, for each artefact, after combining the clouds into a common coordinate system, basic mesh models were developed, Table 5.3. The base models document the appearances, sizes and textures of the elements of the coronation garment of the last Emir of Bukhara and form the basis.

Table 5.3. Base model parameters

No.	Object	Number of triangles, thousands	Size, MB
1	Dressing gown	2,085	150
2	Salla - turban	280	20
3	Kaushi left	312	20
4	Kaushi right	320	20
5	Mahsi left	830	57
6	Mahsi right	850	59

In the “Developing target models” stage (the “Dissemination” phase (Fig. 5.63) a model was developed for disseminating the models to the Internet through a 70% and 85% reduction in the number of triangles. This allowed to reduce the size of the models to about 20% of the base. These models were used to develop the model of the coronation costume of the last Emir of Bukhara by combining (in the digital space) all its elements (Fig. 5.65).

Dissemination models were used to present the coronation costume of the last Emir of Bukhara on the Internet: https://silkroad3d.com/?page_id=2659.



Fig. 5.65. Dissemination model of the coronation costume of the last Emir of Bukhara. By the authors

Conclusions

The obtained results prove that it is possible to 3D scan garments with SLS, even if they are embroidered with shiny gold thread. The scanning process itself requires considerable human resources (museologists and IT specialists) and time.

In the course of the work, the following problems were diagnosed that should be considered and corrected:

- Some museum artefacts cannot be removed from the showcases (for various reasons, e.g. the showcase cannot be dismantled (glued), the key is missing, the artefact attached inside the showcase cannot easily be dismantled, the person responsible for the given part of the exhibition is unavailable, etc.).

- Costumes require support structures after removal. They are not always available in the museum. The use of ad-hoc construction (e.g. a head of a museum employee) is not always a good solution (for example, in the turban scan there was as much as 5% of the shortage of external space, and in the dressing gown only 0.2%).
- Difficulties in access to electricity (e.g. extension cords or even mobile battery power supplies) should be anticipated.
- Select the scanning site appropriately, avoiding gusts of air (such as drafts, air conditioning, or the movement of tourists) that may change the position of the fabric.
- The museum staff should be actively assisted.

The developed methodology and diagnosed problems allowed for more efficient scanning of clothing in the museums of Tashkent and Urgench in Uzbekistan during subsequent expeditions.

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6. A set of authors' works in the field of digitization and sharing of cultural heritage objects

The attached list of publications concerning the digitisation of cultural heritage objects and their archiving and dissemination, including those from outside the Silk Road area, was downloaded from the publication database of university employees in the Scientific and Technical Information Centre of the Lublin University of Technology.

The works discussed were created with the cooperation of many younger colleagues from the LUT Department of Computer Science and colleagues from many universities in the area of the Silk Road. All of them were inspired by the authors of this area of scientific research and thus became part of the activities of an informal scientific and research school concerning the creation of digital 3D models for archiving and sharing objects of tangible cultural heritage.

2022

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9. *Computer technologies in sharing the cultural heritage and education of the Silk Road from Uzbekistans*, eds. by **Montusiewicz J.**, Abdullaev U., Lublin: Wydawnictwo Politechniki Lubelskiej, 2022, 256 p., ISBN: 978-83-7947-516-2, <http://bc.pollub.pl/dlibra/publication/14100> (accessed on 20 August 2022).
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Marek MIŁOSZ, creator of the Laboratory of Motion Analysis and Interface Ergonomics and head of the Division of Software Engineering and Database Systems. Since 2017, he has been actively cooperating in the field of application of 3D computer technologies in the field of archiving, popularisation and sharing of material cultural heritage. Co-organiser and participant of all scientific expeditions to the countries of Central Asia in the years 2017–2022. He works as a teaching professor in the Department of Computer Science of the Lublin University of Technology.

Jerzy MONTUSIEWICZ, head of the Division of Programming and Computer Graphics and creator of the Laboratory of Intelligent System Programming and Computer 3D Technology (Lab 3D). His scientific activity concerns the use of 3D digitisation in archiving and sharing objects of tangible cultural heritage. He is the co-author of many research papers on this subject and the co-organiser of all scientific expeditions to the countries of Central Asia in the years 2017–2022. He works as a professor in the Department of Computer Science of the Lublin University of Technology.



Jacek KĘSIK, employee of the Division of Programming and Computer Graphics and of the Laboratory of Intelligent System Programming and Computer 3D Technology (Lab 3D). His scientific activity concerns the use of 3D digitisation in archiving and sharing historic objects. Specialist in the field of 3D scanning and data post-processing. Participant of many scientific expeditions to the countries of Central Asia during 2017–2022. He works as an assistant professor in the Department of Computer Science of the Lublin University of Technology.

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