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Structured-light 3D scanning of exhibited historical clothing—a first-ever methodical trial and its results

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Abstract

Historical costumes are part of cultural heritage. Unlike architectural monuments, they are very fragile, which exacerbates the problems of their protection and popularisation. A big help in this can be the digitisation of their appearance, preferably using modern techniques of three-dimensional representation (3D). The article presents the results of the search for examples and methodologies of implementing 3D scanning of exhibited historical clothes as well as the attendant problems. From a review of scientific literature it turns out that so far practically no one in the world has made any methodical attempts at scanning historical clothes using structured-light 3D scanners (SLS) and developing an appropriate methodology. The vast majority of methods for creating 3D models of clothes used photogrammetry and 3D modelling software. Therefore, an innovative approach was proposed to the problem of creating 3D models of exhibited historical clothes through their digitalisation by means of a 3D scanner using structural light technology. A proposal for the methodology of this process and concrete examples of its implementation and results are presented. The problems related to the scanning of 3D historical clothes are also described, as well as a proposal how to solve them or minimise their impact. The implementation of the methodology is presented on the example of scanning elements of the Emir of Bukhara's costume (Uzbekistan) from the end of the nineteenth century, consisting of the gown, turban and shoes. Moreover, the way of using 3D models and information technologies to popularise cultural heritage in the space of digital resources is also discussed.

Introduction

Digitisation of cultural heritage objects is a method of preserving their appearance in binary form, which can be automatically processed using computer techniques. Like any digital product, binary information on cultural heritage objects can be easily and cheaply reproduced, stored, transmitted, processed and made available. By reproducing it cheaply and storing it in many places in the world, it is virtually indestructible as long as our civilisation continues to function. It is an important element in protecting cultural heritage. In addition, the abovementioned benefits of managing digital representation of cultural heritage objects make their dissemination easier and cheaper, and allow a wide use of modern information channels, like the Internet.

Documenting cultural heritage requires not only high precision, but also geometrically accurate mapping of the shape. This mapping is the basis for its

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cataloguing, reproduction, renewal, popularisation, and if necessary, and reconstruction.

In recent years, technological development in the area of information technology has led to the development of digitisation systems, on the one hand, and the possibility of a wide reception of digital information by practically the whole society, on the other. The technological development of digitisation systems provides ever newer and newer technical and software tools, increasing the possibilities of using them and lowering the costs of 3D digitisation and dissemination. In the era of universal access to the Internet and the fact that members of society have computers and mobile devices with great possibilities of processing and presenting data, a wide market has emerged for recipients of digital information about cultural heritage sites.

Registration of cultural heritage objects by technical means began with the invention of photographs. Previously, this was only possible through manual human activities—sketches, paintings or verbal descriptions. When photography was invented, which recorded images, it became possible to obtain data about cultural heritage objects in a more automated way. However, it was analogue technology. It reduced the costs of recording and reproducing information, but not enough (at the beginning of the XX century the number of albums published in print reached tens or at most hundreds). Meanwhile, thanks to it, many series of photographs capturing cultural heritage objects were created. An example of such a series is stored in the United States Library of Congress, a collection of S. M. Prokudin-Gorski's analogue colour photographs (sic!) from the early XX century [1]. This collection contains almost 2,000 colour photographs taken between 1903 and 1916 [2]. The photographs were taken across the vast territory of the Russian Empire in a unique technology of colour fixation [2]. Nearly 13% of the photographs from this collection concern the Central Asian part of the Russian Empire (currently these are independent countries, such as: Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan and Kazakhstan). It is one of the first such numerous (over 250 photos) collections of colour photographs from Central Asia of over 100 years ago.

Prokudin-Gorski's photographs capture the appearance of architectural and cultural objects, which are now considered to be cultural heritage objects. They are currently being digitised as part of the International Research Project "The Legacy of S. M. Prokudin-Gorsky" [2], which greatly facilitates wide access to them. Preliminary analysis of the photos shows that about 70% of the photos from Central Asia present people and their appearance, i.e. above all their clothes. They show the (currently historical) costumes of people from different social strata: from the Emir and his officials, through merchants, workers, women to beggars (Fig. 1). Similar actions, but with the use of modern digital technologies, are presented in this article. Unfortunately, costumes from that era can now be found only in museums and private collections, and not on the streets of towns and villages.

Historical costumes are a component of cultural heritage. They are collected, stored and made available in various types of museums. Due to the delicate materials from which they are made, they are particularly vulnerable to damage. Their digitisation will allow them to be preserved for posterity.
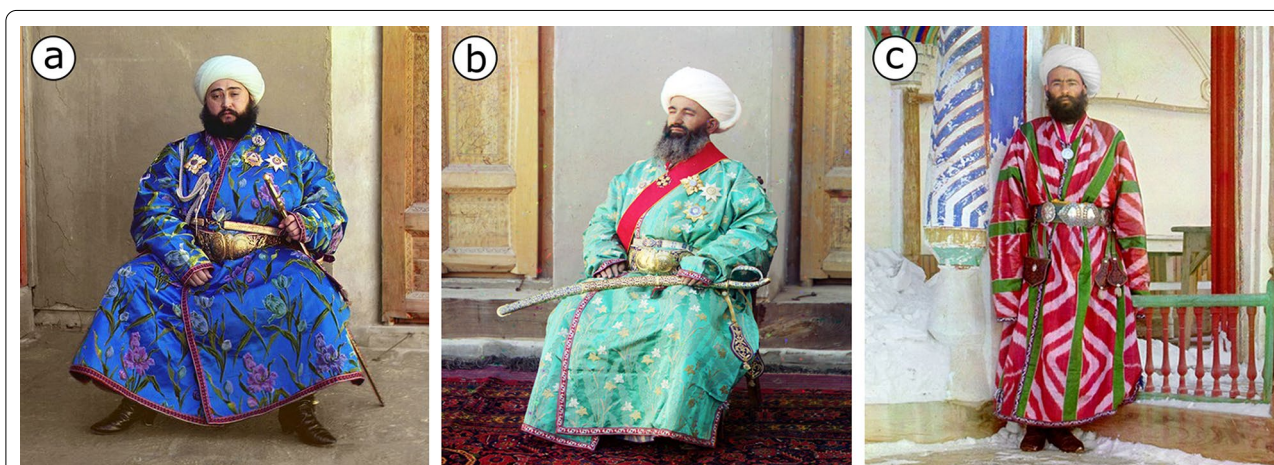
Fig. 1 Photos of people in historical costumes from Uzbekistan (cities of Bukhara and Samarkand) taken by S. M. Prokudin-Gorski [2]: **a** The Last Emir of Bukhara (Mohammed Alim Khan), **b** Prime Minister of Bukhara, **c** Bukhara bureaucrat

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The digitisation of the exhibited cultural heritage objects began with the the era of digital photography and 2D scanning techniques. With technology advancement a third dimension has been introduced. A 3D technology has emerged, together with its implementation techniques.

Nowadays 3D scanning is a fairly widespread technique for acquiring 3D images of cultural heritage artifacts, especially in the areas of small historic objects [3–5], sculptures [6–9] rooms [10, 11] or large buildings and entire architectural sites [12–15].

The 3D scanning process of historical costumes, due to the materials from which they were made, their flaccidity and susceptibility to shape change with the movement of objects, is a much more difficult undertaking than the digitisation of typical museum artefacts from archaeological excavations, such as: destructs of ceramics or clay vessels, stone or bone figurines, elements of jewelry, leather products or metal artefacts—arrowheads or spears, axes, knives and various types of cutting weapons.

Initiatives like European Year of Cultural Heritage, Work Plan for Culture 2019–2022, United Nations Development Programme (Standard 4: Cultural Heritage), as well as other initiatives run by local governments, stress out the importance of sustaining the legacy of the cultural and natural heritage as well as protecting it against destruction by either human natural forces. These motivated museums to draft and implement procedures, and obtain funding needed to digitise their resources and present it in novel ways. Thanks to that, professional and amateur equipment for digitising and visualising resources in the 3D environment (such a way allows not only to preserve the geometry and dimensions of a digitised object, but even make it photorealistic) is constantly growing in number, being easier and, indirectly cheaper to obtain.

Cultural institutions and their associations create digital archives and make them available to a wide audience in the Internet [16–18]. Initiatives similar to Sketchfab [19–21] and Google Arts & Culture [22] emerge and are beeing developed, where 3D models are made available to the general public.

The aim of the article is to present:

- Developed and effective methodology of acquiring 3D scans using manual 3D SLS of various historical elements of clothing in in situ conditions for their documentation and dissemination.
- Ways of solving problems arising during 3D scanning with the use of SLS of individual elements of the costume in the conditions of a museum located in a different cultural area.

- On the example of the costume of Emir Bukhara from Uzbekistan, stages of post-processing of acquired data, which lead to obtaining digital 3D models with different parameters.

Study background

Literature research was conducted in specialised scientific databases, open access databases as well as museum websites and various types of art galleries. Despite finding a dozen or so works (articles, reports on websites, books) on the preparation of digital 3D models of historical costumes and methods of presenting them, it can be concluded that the literature (and Internet) research gave a negative result—no scientific works were found that would pick up the topic of 3D SLS of historical clothes in a scientific manner, dealing with the whole complexity of such a process. There were no scientific papers that would present the procedures for 3D SLS in terms of digitisation of various elements of historical costumes and provide comprehensive information on the technical and organizational requirements for the implementation of these works and their parameters, including such as:

- the number of contractors' team,
- time required to perform a complete scan,
- detailed data of 3D mesh models obtained after post-processing,
- data of final models to be disseminated.

Currently, two main trends can be distinguished for creating digital 3D models of clothing:

- the first is the manual creation of such models using specialised CAD (Computer Aided Design) programs,
- the second is to use various 3D scanning technologies and generate 3D models based on the collected data (in the form of a series of photos or point clouds)

Manual creation models

During the literature research, it was possible to observe that works of numerous authors follow the first trend [23–27]. The authors used the following 3D modelling technologies/tools in the context of historical clothes: CAD software for clothes (like CLO 3D, Gerber AccuMark 3D, Optitex or Lectra Modaris) and general-purpose programming, also for engineering applications (like MeshLab, Blender 3D Creation

Software, AutoDesk 3D or Rhinoceros 3D). Projects related to the construction of 3D models of historical clothes using 2D/3D modelling methods include: rider-skirt for riding in the so-called women's saddle [23], trousers [24], Prince Albert of Saxe-Coburg and Gotha's full-dress suite [25]. In these works, the procedures of activities were presented, distinguishing many detailed stages of drawing 2D models along with providing detailed parameters to obtain 3D models. For example, a model of a gown from Cicero's times, made with this method, placed on a 3D digital dummy, and an animation of the gown draping to make it look realistic are presented in article [26]. Study [27] describes many methods and CAD programs for modelling costumes that can be placed on digital bases (mannequins) created by 3D scanning. Sometimes researchers introduce a short remark that 3D scanning could be one of the methods of the digitisation of clothes.

3D scanning technologies and photogrammetry

The second trend is to carry out a 3D scanning process of a real object, and then to perform appropriate postprocessing of data. Only a few scientific works mention the use of 3D scanners at various stages of the construction of models of robe images. Unfortunately their full potential is not utilised. Literature analysis revealed that they are mostly used in a limited scope, in order to deal with single elements of digitisation instead of the process as a whole, i.e. a 3D scanner is used to obtain the model of a human posture only, clothes digitisation is done another way. This can be called a mixed method or a hybrid method. Examples of the use of such a method are: a woman's folk costume from the Gorenje region (Blender program was used) [28], 3D scanning of the female body in the context of applications in the clothing industry [29], generation of avatar elements (head and body) based on data from scanning 3D and measurements as well as 3D modeling of clothes on the basis of physical, spatial and external information [30], scanning of mannequin torsos to properly reproduce various figures of figures on which manually modeled outfits were placed [31], 3D simulation of historical costumes modeled manually on avatars [32].

The most frequently described and at the same time used technique of 3D digitisation of historical costumes are passive methods: photogrammetry and SfM (Structure from Motion), the fundamental (fundamental) theoretical basis of which can be found in [33]. An example of the application of the SfM technique is the creation of the 3D Jordanian Dress model on the basis of 280 photographs [34]. The photogrammetry and SfM methods use markers attached to the photographed surfaces, additional dimensioned objects (e.g. rulers) or manual measurements of distances between specific points [35]. Their digital deletion from the 3D model is very laborious. Additionally, sticking markers on historical costumes is rarely possible.

The photogrammetry and SfM method was used in work [36]. It shows the presented installation consisting of a digital 3D model of a dress displayed on a transparent screen and a real dress on the Fashion Curation 2013 display (Moving Textiles: Digital Encounters). However, article [36] does not contain any data on the parameters of the presented model. In turn, study [37] describes the 3D digitisation of the dress with the use of specialised Autodesk 123D Catch software developed for iPad and iPhone devices (photogrammetry). The digital 3D model was generated on cloud servers, and the surface and 3D model finishing processing was done in Adobe Photoshop (removing markers placed on the outfit before shooting) and 3ds Max, which was also used for rendering. The paper does not present the parameters of the digital 3D model transferred for presentation purposes to the Unity engine. Website [38] presents examples of 3D models of historical costumes from the turn of the nineteenth and twentieth centuries made by using photogrammetry, but there is no information on the details of the methodology used and the results obtained (model quality, size, etc.). 3D scans are often the source of clothes texture only [28]; sometimes a 3D scanner is used to document the profile, shape and position of textiles in a bundle before conservation [39].

In the available Internet sources (but not scientific ones) several unusual solutions can be found for 3D scanning of historical costumes. Blog [40] describes the use of the specialised medical scanner Vectra WB360 (used to detect skin cancer) to 3D scan the gown of the Australian opera diva Dame Joan Sutherland stored at the Arts Centre Melbourne and transfer its digital model to the VR world. However, there are no details of the generated digital model and data processing methods among the information contained therein. Work [36] presents a digital model of a dress created by scanning by computed tomography (CT) to show the inner layers of a dress invisible to the eye (Fashion Curation'13 display). Hu et al. [41] presented an interesting solution, although on the example of contemporary casual clothes, as they used Kinect Fusion to scan a person wearing the clothes and then only model the extracted garments. Tota et al. reported using a Konica Minolta Vivid 910 3D laser scanner to obtain a model of a Luma Waistcoat, although they provided a scanner model and print screens of the coat

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model only [42]. One work reported the model being a result of 3D laser scanning [43], but further details were missing, even the scanner model. Some authors just mention that they have a model being the result of scanning, but it is unsure whether the authors mean photogrammetry as 3D scanning. On the website [44] you can find a report on the use of a 3D laser scanner (FARO scanner head mounted on the manipulator's arm) to scan the mummy of a Peruvian woman from 1700 years ago, whose digital image was used to recreate her face. However, the presented physical generated 3D models of a bust of a woman wearing a dress, jewelery and a metal headgear was, however, only an archaeological staging [44].

3D SLS of museum artifacts are presented on Russian websites [45, 46], however they do not contain digitization of historical costumes. They concern the collection of porcelain human figurines in folk costumes (Museum of the Imperial Porcelain Factory in Saint Petersburg). The costumes of these figures are not made of fabrics but painted on the surface of the figures. Colorful costumes were painted by hand on the copies of the figures made by 3D printing. On the website [47] you can see scenes from Chinese history, for which both 3D SLS (EinScan-Pro scanner by SHINING 3D) and 3D printing were used. After appropriate processing, 3D models of scanned people in costumes (presumably copies) were printed out as monochrome objects and painted by hand. There is no information in the text about the quality of the digital 3D model of the scanned costumes and the 3D scanning procedure used. On the blog [48] you can find reports of attempts to 3D scan various museum artifacts, including historical costumes, using SLS scanners (Artec Space Spider and Artec Eva). Apart from the information on the average scanning time of a single object of about 15 min and information on what objects could not be scanned (e.g. the umbrella was scanned on one side only, because after turning over, the position of the fabric folds changed, which is a typical problem when scanning fabrics), there are no procedural indications about the digitisation of objects and their further processing. In this case, it was not possible to properly design and apply a methodical approach to 3D scanning that would take into account such a threat. From the content of the Museum of Applied Arts & Sciences blog [49] you can learn that the SLS 3D scanner (Artec Eva) was used to create a digital 3D model of samurai armor, which was enriched with an interactive touch interface through the use of specialised software. However, no methodological information was provided that would allow others to carry out similar activities, as well as the data of the generated digital model. The work [50] describes tools for 3D scanning and programs for the preparation of digital 3D models that are used in museology, but no rules of conduct or procedures for 3D scanning of museum artifacts, especially historical costumes, are presented.

Conclusion of the literature review

In conclusion, a review of the available scientific literature and Internet sources can be concluded that very few works are devoted to 3D scanning of historical clothes using 3D scanners, especially those based on structural light technology. Works that were identified during the query show that the whole potential of 3D scanners is not used. No scientific approach to this topic exists either; what is more, authors do not deal with the whole complexity and methodology of scanning very diverse clothes of different shapes and materials. Results are usually not presented and analysed properly. All of this makes a lot of room for work. This is due to the fact that various reports of 3D scanning of historical costumes or theatrical costumes of high historical significance, which can be found in scientific and online resources, are not research-based and do not contain detailed information about the scanning process and the results obtained. There are definitely no available procedures describing the individual stages of activities necessary to perform 3D SLS of historical costumes in working conditions in situ, which would become mini guides allowing museum employees to independently digitise historical costumes in the future.

Research question

It seems that so far no one has used, in a methodical way, 3D scanning techniques using structured-light technology methods to obtain data on the appearance of historical clothes. Meanwhile, in the course of literature research, a number of potential problems in 3D scanning of historical clothes in in situ conditions were identified, such as: providing logistical support by museum employees, the way of displaying items of clothing during digitisation (including ensuring their stability and accessibility to the surface), limited access time to clothes, sensitivity of objects to damage, difficulties in acquiring data with too high gloss and transparent decorative elements made of precious and gilded stones. In order to fill the identified gap, it seems reasonable to pose the following research question:

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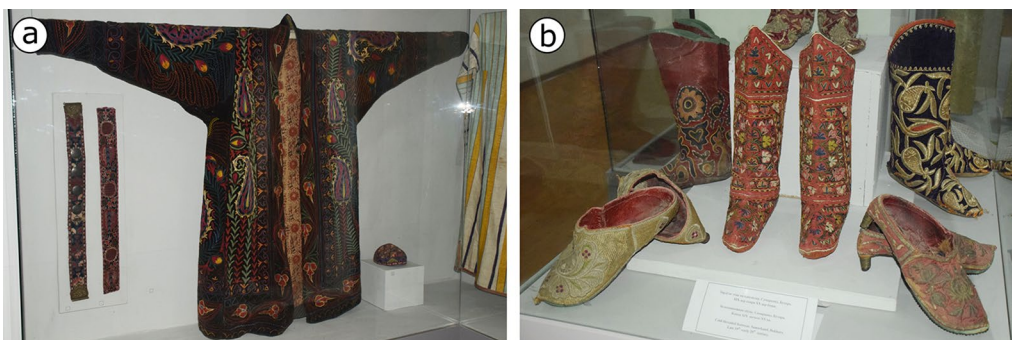
Fig. 2 The classic way of presenting clothes in museum display cases: at the wall (**a**) and in the centre of the room (**b**)

Is it possible to efficiently acquire **in situ** ***3D digital data of historical clothing using 3D structured-light scanners for their documentation and dissemination?***

The term "efficiently" is used to mean that such activities can be effectively carried out in situ with limited technical resources, limited human resources and limited access time to the facilities.

The authors undertook to develop a methodology of 3D SLS of historical clothes and processing the results using modern devices and software. The methodology was tested on the example of a scan of the nineteenth century costume of the Emir of Bukhara (Uzbekistan).

Methods and materials
Determinants of 3D SLS of historical costumes

In the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Samarkand, Uzbekistan) traditional costumes from Uzbekistan are presented in a classic way, i.e. in showcases placed against the walls (Fig. 2a) or in the centre of the exhibition hall (Fig. 2b). Unfortunately, glass is a significant obstacle in 3D scanning using structured light.

SLS through a glass surface is in principle possible, but the presence of a barrier in the form of a display case significantly hinders the correct positioning of the scanner in relation to the scanned object, which

Fig. 3 Methodology of 3D SLS of historical costumes

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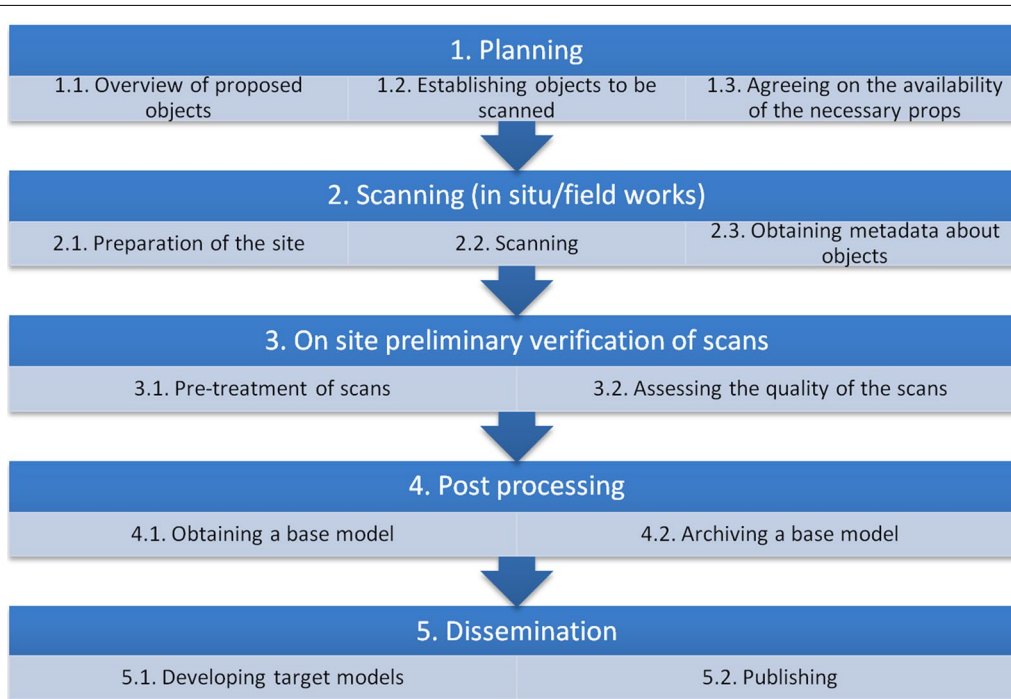
makes it difficult or impossible to properly scan all its surfaces. In addition, the panes have defects, scratches and dirt, which also negatively affects the scanning process. The location of the display cases against the wall usually makes it impossible to reach the back of the exhibits. Display cases located in the centre of the room have elements connecting glass panes and/or corners, which also constitutes a significant obstacle in scanning. Therefore, the exhibits must be removed from the showcases. This is a specific organisational problem.

Proposed methodology of 3D scanning of historical costumes

Figure 3 presents a diagram of the developed methodology of 3D SLS of historical clothes and processing the results using modern devices and software.

The methodology consists of 5 stages (Fig. 3).

Stage 1 (Planning) of the methodology is carried out before the actual scanning session. It can be implemented on site as well as through remote arrangements. During it, the following sub-stage tasks are performed:

- At stage 1.1, the sites proposed by the cultural heritage (CH) institution for scanning are analysed. In the case of remote arrangements, photos of objects are transferred. Scanning technicians analyse objects in terms of the required scanning techniques, in particular: the way the object is arranged during scanning, the required lighting, additional positioning surfaces. The potential for obtaining the desired scan is also assessed.
- At stage 1.2, objects that will be scanned are selected. The objects indicated in step 1.1 can be rejected by both the scanning technicians (due to the inability to obtain the desired scan quality) and the CH institution's refusal to use 3D SLS techniques due to the potential harm to the exhibit by activities consistent with the methodology (Fig. 3). For example, the fabric of a garment is too delicate to be removed from the display case and placed in the required position.
- At stage 1.3, the details of scanning selected objects are agreed. Depending on the requirements, the availability of the necessary props (dummy, lighting, desktop, etc.) is determined. Stage 2 (Scanning) of the methodology covers the proper implementation of the scanning process. The objects in the order agreed with the CH facility are made available and the procedure of their scanning is carried out, which includes cyclically performed task sub-stages:

- At stage 2.1, the scanning station is prepared for a given object (lighting setting, dummy, possible suspension, etc.). The object is placed in the position.
- Stage 2.2 covers the actual procedure of the scanning process. Individual partial scans are performed. Scanning must be performed ensuring that the orientation of the fabric of the scanned object remains unchanged until the entire procedure is completed.
- Stage 2.3 includes collecting information about the scanned object (textual and visual – photographic data). They are necessary both for the correct identification of the obtained scans, as well as in processing data from the scan, as an aid in positioning and determining the correct colour of the obtained model.

Stage 3 (On site preliminary verification of scans) is carried out for each object at the place and time of scanning in order to make sure that the 3D SLS process is running correctly. This avoids the need to re-prepare the object for the scanning process in the event of any irregularities in the acquired data. It includes the following sub-steps:

- Stage 3.1 includes pre-processing of sub-scans by the technician. It includes assessing the quality of individual scans and matching parts to each other. The completeness of the acquired point cloud is also analysed.
- Stage 3.2 includes the decision to accept the obtained effect. If you obtain a scan of insufficient quality or completeness, you may decide to repeat some or all of the scanning process. In special cases, it may be decided not to scan a given object. Representatives of CH institutions may participate in this process.

Stage 4 (Postprocessing) is performed after the scanning session is completed. It does not require the involvement of CH institutions. At this stage, the pre-merged data from stage 2 is fully processed in order to obtain the base model and its archiving. During it, the following sub-stage tasks are performed:

- Stage 4.1 consists in the processing of scans (cleaning, micro-matching of clouds, etc.) and generation of the model with the highest available parameters (the so-called Base Model). At this stage, apart from the scans themselves, metadata (photos etc.) obtained at stage 2.3 are used. They are especially helpful when matching a large number of

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partial scans of surfaces with a similar fabric pattern.

- Stage 4.2 includes archiving both processed scans (to enable further analysis) and the Base Model, saved in universal formats that can be processed with various software.

Stage 5 (Dissemination) includes disseminating the obtained model in the forms required for a given application (e.g. presentation on websites). It can be implemented many times, depending on the needs, using the Base Model. Stage 5 consists of the following substage tasks:

- In step 5.1, the Base Model is converted to Dissemination Models in accordance with the specified requirements (format, model complexity, size, texture type, location, lighting etc.).
- Stage 5.2 includes the publication of the Dissemination Models in the appropriate media. The publication is also accompanied by supplementing the information about the presented object on the basis of metadata obtained at stage 2.3.

The developed methodology of 3D SLS of historical clothes and processing of the results was tested in the field at the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Samarkand, Uzbekistan) during the scanning of the Emir of Bukhara's costume.

The Emir of Bukhara's outfit

The Emirate of Bukhara existed as an Uzbek state from 1785 to 1920. In the years 1873–1917 it was under the protectorate of the Russian Empire. It was located in central Asia in the lands of present-day Uzbekistan, Tajikistan and Kazakhstan. It was liquidated by the Soviet Red Army in September 1920. The last Emir of Bukhara, Said Mir Mohammed Alim Khan (Fig. 1) emigrated to Afghanistan [51, 52], where he died.

The Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Samarkand) stores elements of the Emir of Bukhara's costume (at least that is what museum staff and guides call it), such as (Fig. 4):

- Dressing gown, gold-embroidered, Bukhara, 1895.
- *Salla* (turban), a man's head bandage from fabric, Bukhara, end of the XIX century.
- *Mahsi* and *kaushi* (high and low shoes), Bukhara, end of the XIX century.

These elements were selected for scanning and verification of the procedure from Fig. 3. The choice was not accidental. These objects vary in size and materials: from thick dressing gown fabric, richly embroidered with gold thread, to thin turban fabric. This made it possible to check the proposed methodology of 3D SLS historical costumes on artefacts that differ significantly in surface textures and materials.

Fig. 4 Objects selected for 3D scanning: **a** dressing gown, **b** turban (salla), and **c** shoes (mahsi and kaushi)

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Fig. 5 Preparation of objects for 3D SLS: **a** taking the outfit out of the showcase and **b** wrapping a turban on the head of a museum employee

***Scanning elements of the Emir of Bukhara's costume* in situ**
The scanning was carried out by a team of three IT specialists (IT team), the authors of this article. It covered the first three stages of the developed methodology (Fig. 3).

While obtaining and processing the data, the following equipment and software were used:

- *hand-held structured-light technology scanners (Artec Eva – 50-100 microns accuracy, saving textures),*
- *digital camera (Nikon D7200),*
- *laptop (i7 Processor, 32GB RAM, GTX 980 8MB graphics card),*
- *rotary scanning table with reference surface,*
- *software on site (Artec Studio 12 Professional),*
- *post-processing software (Blender v2.8, MeshLab v2020.04).*

The visit to the museum was previously agreed by the persons who acted as intermediaries, but the IT team and the museum staff could not agree on any details of the operation due to the lack of a direct meeting. All actions were taken on the basis of the experience of

Fig. 6. 3D SLS of the elements of the Emir's costume: **a** dressing gown, **b** turban—salla, **c** kaushi—low shoe and **d** mahsi—high shoe

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Table 1 Set of activities related to the 3D scanning process of the Emir's costume

No	Activity	Team	Completion time
1	Arriving at the museum, formal matters, closing the exhibition	IT team, 3 people	13:12 (14 min.)
2	Preparatory activities		
2a	Taking the exhibits out of the display case	Museologists, 6 people	13:26 (10 min.)
2b	Preparing the equipment	IT team, 3 people	(7 min.)
3	The outfit		
3a	Scanning the outfit	IT team, 2 people	13:36–13:48 (12 min.)
3b	Creating photographic documentation	IT team, 1 person	(10 min.)
4	The turban		
4a	Preparing the turban	Museologists, 4 people	13:43–13:53 (10 min.)
4b	Scanning the turban	IT team, 2 people	13:55–14:00 (5 min.)
4c	Creating photographic documentation	IT team, 1 person	(15 min.)
5	The low shoes		
5a	Scanning the low shoes (2 items)	IT team, 2 people	14:02–14:08 (6 min.)
5b	Creating photographic documentation	IT team, 1 person	(6 min.)
6	The high shoes		
6a	Preparing the tripod	Museologists, 1 person	14:03–14:08 (5 min.)
6a	Scanning the high shoes (2 items)	IT team, 2 people	14:10–14:20 (10 min.)
6b	Creating photographic documentation	IT team, 1 person	(10 min.)
7	Packing the equipment, opening the exhibition	IT team, 3 person	14:21–14:26 (5 min.)

the IT team, and the museum staff improvised solving emerging problems in real time.

Some activities were carried out in parallel by both teams (museologists and the IT Team), including the initial verification of the quality of the obtained scans (stage 3 of the methodology in Fig. 3).

Removing the outfit from the sealed display case turned out to be quite a difficult undertaking due to the fact that the design of the display case did not provide for free access to the objects placed there (Fig. 5). When removing the ball from the stand, it was dissolved. Thanks to the cooperation of both teams and the willingness to make 3D scans of all the elements of the outfit (Fig. 6), the emerging problems could be overcome there and then. For example, the human head dummy unavailable in the museum was replaced by one of the museum employees (Fig. 6b).

The scanning time was minimised due to the fact that the exhibition room was closed to normal visitors at the time of scanning. It is not a comfortable situation for the museum authorities in view of the large number of visitors in organised tours with a strongly limited time window and the programme of visiting the museum during its normal opening hours. One of the requirements of the museum board to minimise the time of data acquisition was to make the exhibition available for scanning. The total stay in the museum from entering it until leaving took only 1.5 h (Table 1).

The activities related to the object preparation, scanning and photographic documentation process are listed in Table 1. Other activities performed at the same time by the IT team, which were parallel to the digitalisation process, were omitted, such as: (i) discussing with a team of museologists how to display subsequent items for digitisation, (ii) collecting information about scanned items (the need to search for specialised vocabulary and translate them (Polish/English/Russian/Uzbek), (iii) backup files from scanning and checking their quality on a current basis on a second computer set. Some of these activities were performed when the team from the museum was preparing subsequent objects for scanning (Tables 1, 4a, 6a).

Note that the scanning time is not linearly related to the size of the scans obtained. This is due to the different shapes of the scanned items. The dressing gown contains large, relatively flat surfaces, which facilitates and speeds up the scanning process. The rest of the garment is smaller in size and has a lot of edges. Passing during the scanning over the edge with a significant difference in the angle of the joined surfaces requires increased attention to avoid loss of scanner positioning in relation to the scanned object. Consequently, it extends the scanning time of such an area. In the case of objects with a very small area (Kaushi), it was necessary to support the scanning process with an

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Fig. 7 Clouds of obtained dressing gown points before merging

appropriate reference surface (Fig. 7c), ensuring that the scanner was positioned.

Postprocessing

The obtained 3D scans of individual elements of the outfit were post-processed in order to obtain the required models—stages 4 and 5 of the methodology developed (Fig. 3). This process consisted of stages that slightly differed depending on the model being processed. This was due to different techniques of obtaining scans for individual objects. Generally, there are three steps of post-processing.

At the first step, individual partial scans were analysed and purified from undesirable fragments. The specificity of scanning with the use of a handheld scanner means that there is a risk of distortions when positioning the moving scanner, which causes the formation of "delamination" of the scanned surfaces. The occurrence of such a case had to be caught and the dissection corrected. Correct scans could then be fitted by comparing the surface of point clouds. The final effect of the first stage was clean and distortion-free partial scans, matched to each other—a comprehensive point cloud. Point clouds of individual elements of the outfit were saved in the native Artec Studio software format.

At the second step, the overall model point cloud was converted to the mesh base model. The generation of the mesh model was carried out by Artec Studio software dedicated to the scanner. The interference of
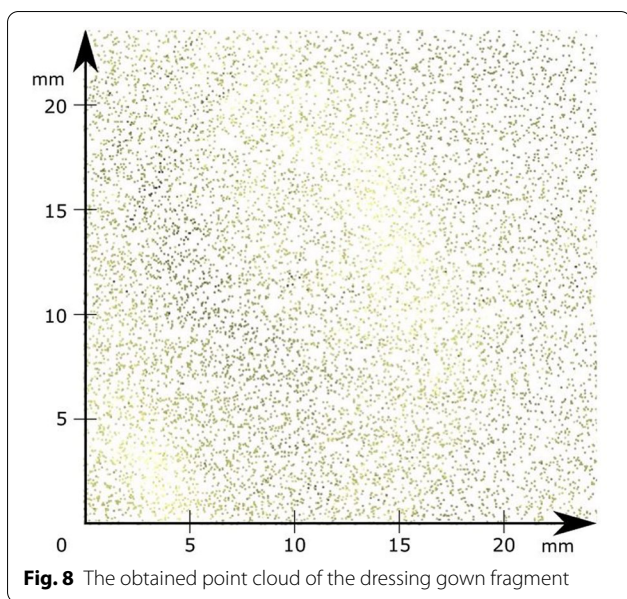
Table 2 Parameters of elements and the results of their scanning

No	Articles of the Emira's costume	Number of partial scans	Geometric sizes of objects and total approximate surface area	Total size of the scan
1	Scanning the dressing gown	8	robe sides: $2 \times (47 \times 130)$ cm, robe back: 95×130 cm, sleeves: $2 \times (2 \times 65 \times 26)$ cm, około: $31,000$ cm^2	3.5 GB 83.63 million points
2	Scanning the turban (*salla*)	4	diameter: 20 cm, average height: 20 cm, average surface: 1250 cm^2	0.5 GB 8.73 million points
3	Scanning the low shoes (*kaushi*, 2 items)	$5 + 3$[a]	length: 29 cm, average height: 7 cm, average sole width: 8 cm, about: $630 \times 2 = 1260$ cm^2	0.6 GB $+$ 0.5 GB[a] 17.05 $+$ 15.23 million points[b]
4	Scanning the high shoes (*mahsi*, 2 items)[c]	$6 + 4$[a]	length: 29 cm, height: 45 cm, average width: 14 cm, average sole width: 8 cm, about: $1900 \times 2 = 3800$ cm^2	0.6 GB $+$ 0.45 GB[a] 14.02 $+$ 7.72 million points

[a] scanning the second piece (knowledge from scanning the first piece was used)

[b] scans include the surface of the rotary table on which the *kaushi* was scanned

[c] scanning required changing the position of the shoe (position on its side) on the rotating table

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Fig. 8 The obtained point cloud of the dressing gown fragment

Fig. 9 Base Model of the object **a** dressing gown and **b** fragment of the model with the mesh of triangles shown

a IT specialist consisted, among others, in on the decision on the method of possible filling of the discontinuities in the surface of the obtained model. In the next step, the colour information about the surface of the object recorded in partial scans was transferred to the base model of the scanned object with the simultaneous unification of the brightness levels. IT specialist corrected the parameters of the target colours to ensure faithfulness to the original colours, using reference photos of objects. The base model was saved in the universal.obj format, while the texture in the lossless.png format.

The third step involved the preparation of various versions of the object model intended for dissemination, the so-called Dissemination Models. It was necessary to simplify the Base Model mesh to ensure the model's availability to a wide audience by minimising download time and hardware requirements. The conversion of the Base Model into various versions of

Dissemination Models was carried out with the use of Meshlab and Blender software. Depending on the needs, a reduction was carried out by up to 85%, i.e. up to 15% of the number of triangles in the Base Model. The.obj model format was retained due to its universal nature. The texture covering the model was also optimised by possible resolution reduction and saving in a lossy.jpg format.

Results
### Obtained materials about the Emir's robes
As a result of the scanning, 30 point clouds (Table 2) with a total volume of over 6 GB were obtained. The total number of points in the clouds (Table 2) was over 146 million. Detailed parameters of the acquired images of elements of the Emir's costume are presented in Table 2.

The obtained materials are in the form of point clouds distant from each other by approx. 0.25 mm, which reflect the geometry of the objects and information about the colour of their surface (Fig. 7). Figure 8 shows a fragment displaying the distribution

Table 3 Base model parameters of elements of the Emir's costume

No	Object	Size of the base model		Estimated percentage of shortages of external area, %[a]
		No. of triangles	MB	
1	Dressing gown	2,085	150	0.2%
2	*Salla*—turban	280	20	5.0%
3	*Kaushi* (L&R)—low shoes	312	20	0.5%
		320	20	1.0%
4	*Mahsi* (L&R)—high shoes	830	57	3.0%
		850	59	5.0%

[a] non-visible surfaces (interior of the dressing gown, interior of the shoes, etc.) are not taken into account
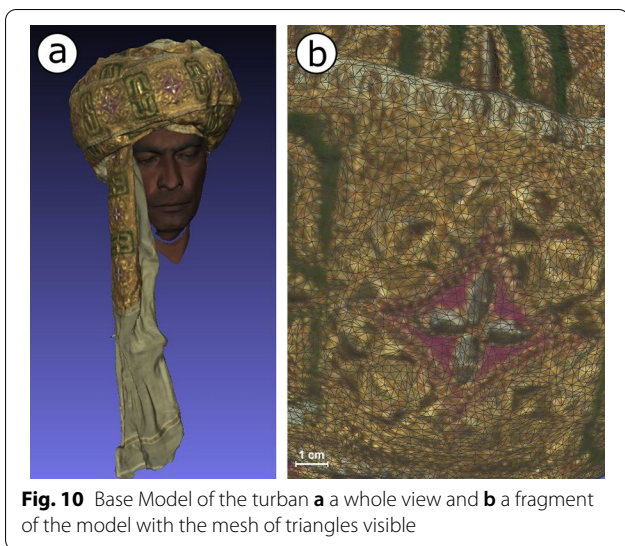
Fig. 10 Base Model of the turban **a** a whole view and **b** a fragment of the model with the mesh of triangles visible

Fig. 11 Base Models of footwear **a** high shoe, **b** low shoe and **c** a fragment of the model with the mesh of triangles visible

of points on the material surface. It can be seen that the sampling density is uniform. Consequently, any

protrusions resulting from the patterns sewn will be visualised with the same accuracy.

Base models—results of postprocessing for data archiving

In the course of processing point clouds, mesh base models of individual elements of the outfit were obtained. The mesh density was selected to obtain the greatest possible accuracy of mapping the surface of costumes determined on the basis of point clouds. Table 3 shows the sizes of the obtained meshes (the number of triangles) and the sizes of the resulting files saved in the universal.obj format (MB).

The dressing gown object was characterised by a large surface, devoid of hard-to-reach fragments. Therefore, the obtained model has the lowest gaps coefficient (gaps) in the continuity of the 3D model surface—percentage of external surface defects (Table 3). Figure 9 shows the Base Model of the dressing gown (with a fragment of the mannequin left as a reference to the shape of the character wearing the garment).

The obtained base model of the turban object is characterised by the highest percentage of shortages. It results from the necessity to adjust the scanning method to the shape instability of the object. The adhesion of the turban belt to the human model torso made it impossible to obtain its inner surface. Figure 10 shows the view of the Base Model of the turban (along with the model's head mapping left as a reference for the correct headgear positioning).

In the case of the low shoes, scanning was carried out using a rotary table with a reference surface. A significant level of shortages in the case of the high shoes (Table 3) results from the inability to scan the surface under the flaps—the unrolling of the flaps was not allowed by the employees of the CH institution. The visible surface of the objects was mapped with a precision equivalent to the previous objects (Fig. 11).

Table 4 Object optimisation in scan processing—dissemination model parameters

No.	Object	Size of dissemination model after optimisation (reduction by 70% of the number of triangles), MB	Size of dissemination model after optimisation (reduction by 85% of the number of triangles), MB
1	Dressing gown	64.8	31.6
2	*Salla*—turban	8.2	4.1
3	*Kaushi* (L&R)—	8.7	4.3
	low shoes	8.9	4.4
4	*Mahsi* (L&R)—	23.1	11.3
	high shoes	23.8	11.7

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Fig. 12 Dressing gown: **a** Base Model, **b** Dissemination Model—70% reduction, **c** Dissemination Model—85% reduction
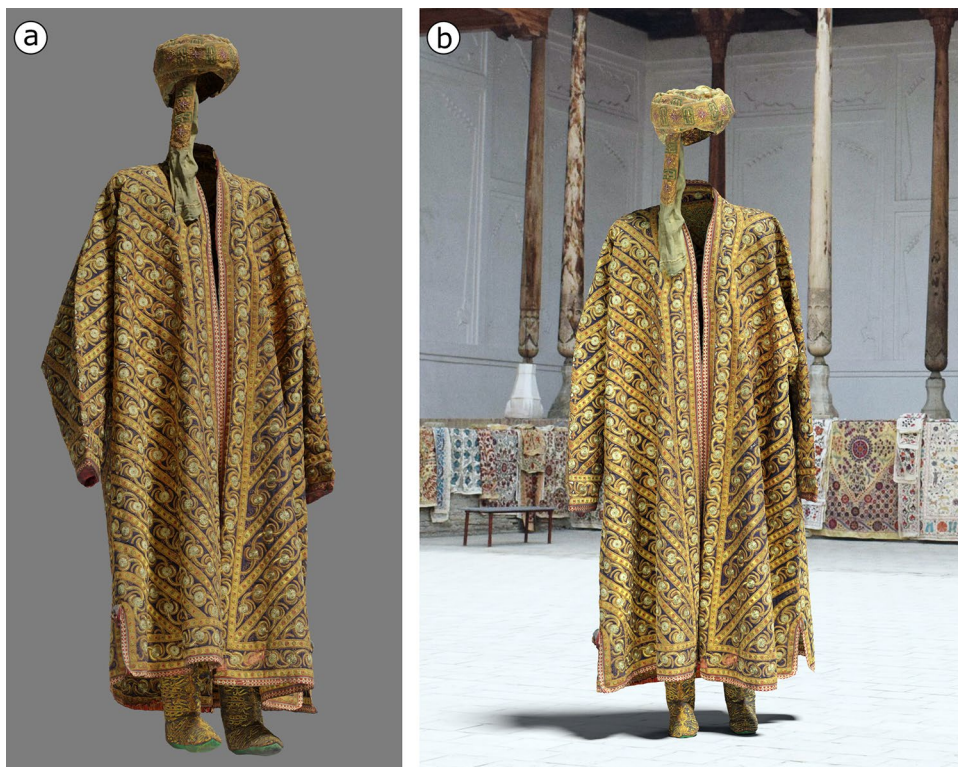
Fig. 13 Dissemination Model of the image composed in Blender and Meshlab **a** combining all elements of the Emir of Bukhara's robe—integrated Model and **b** in the natural scenery of the throne room of the palace located in the Ark of Bukhara—a massive fortress

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Table 5 Problems and solutions of scanning historical clothes—a case study of the dressing gown

Object	Problem	Solution	Alternative
Dressing gown	Large object	Due to the large surface area of the coat, the scan was performed on a display mannequin. Thus it was possible to obtain: (i) no material interference with the display position of the garment, (ii) minimising deep bends and pits in the material surface, (iii) high cohesion of the outer surface of the garment at the level of about 0.2%, losses and defects were practically negligible, (iv) only a slight decrease in the quality of texture acquisition inside the material deflection	Scanning the garment unfolded. This would eliminate sagging and texture inaccuracies. The effect obtained would not necessarily fully correspond to the original However, this approach introduces many new problems, such as: (i) permission from the museum management to unfold the robes, (ii) having a top of the right size to spread the robe out, (iii) difficulties in putting together the scans representing the front and back of the garment, (iv) loss of depiction of garment arrangement over the figure, (v) the need to use simulation techniques for applying material to a virtual form—increased labour intensity, (vi) difficulties in selecting parameters describing the mechanical properties of a garment with a complex structure (fabric warp, sewn-on tapes, convex golden thread embroidery, etc.)

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Dissemination models—the results of processing for dissemination

The basic method of disseminating the obtained models, agreed with the CH facility, was to present them in the Internet. It was necessary to take into account the requirements of matching models to the needs and capabilities of potential recipients, not necessarily having high-performance computers capable of smoothly displaying 3D objects with complexity at the level of the Base Models. It was equally important to limit the size of model files due to the need to transfer them via the Internet. In order to develop Disseminations Models, the meshes of the Base Models were optimised to ensure a satisfactory visual quality while meeting the above-mentioned requirements. Table 4 summarises the obtained model file sizes using 2 levels of mesh detail reduction (i.e. reducing the number of triangles making up the Dissemination Models in relation to the Base Models)—70% and 85%.

Although the obtained Dissemination Models lost the surface details defining the shape of the embroidery on the garment, the visual effect was kept at a good level thanks to the texture. However, in the case of the presentation of models using dynamic shadow techniques, only the shadows resulting from the arrangement of the folds of the garment will be reproduced without shadows on the edges of embroidery. Figure 12 presents a summary of the dressing gown model in three versions of the density of the triangle mesh.

Dissemination Models are available in a 3D view on the website of the Laboratory of Intelligent Systems Programming and Computer 3D Technology (Lab3D), Department of Computer Science, Lublin University of Technology [51]. In addition, the simplified 3D model of the dressing gown was also used to build the virtual exhibition presented in [53].

An alternative method of disseminating the results of the work was to prepare the combination of high-resolution images of the obtained Base Models into an Integrated Model. The generated images of the Integrated Model, including lighting and shadows, were superimposed on the scenery corresponding to the historically presented clothing and simplified to the Dissemination Model format (Fig. 13).

The generated images of the Integrated Model are available in 3D view on the Lab 3D website [54].

Discussion

In the course of scanning the historical clothes displayed at the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Samarkand), a number of problems emerged (both foreseen and unexpected) that could be solved to a greater or lesser degree. They are listed in Tables 5, 6, 7 and 8 together with alternative solutions.

The analysis of the problems and their resolution during the scanning of historical clothes at the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Samarkand), as well as of alternative activities, shows the complexity and variety of problems arising during its course.

Summary

The methodology developed and implemented in the present case study at the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve (Samarkand, Uzbekistan), primarily due to its results of use, allows to answer the research question:

Is it possible to efficiently acquire in situ *3D digital data of historical clothing using 3D structured-light scanners for their documentation and dissemination?*

The answer to the research question posed above is: YES, it is possible to effectively acquire scans of historical clothes using 3D SLS for their documentation and dissemination.

The authors' experience gathered during the experimental work carried out at the Samarkand State Integrated Historical-Architectural and Art Museum-Reserve entitles them to formulate the following conclusions:

- Collecting available information on good practices in the process of 3D digitisation of museum artefacts, arranging them and adapting them to the requirements of in situ digitalisation of historical costumes has resulted in the development of a comprehensive methodology of 3D SLS of historical costumes in the form of a diagram. The developed methodology is addressed not only to researchers dealing with the methods of digitising objects of tangible cultural heritage, but also to museum professionals who in the future should take on the task of 3D digitisation of museum artefacts.
- The prepared methodology clearly separates the organisational and preparatory tasks performed by the museum employees from the activities of a specialised team to conduct 3D scanning and preparation of supplementary photographic documentation. Thanks to this, both teams can work autonomously and fully professionally, which enables parallel work and economical time management. The works carried out at the museum show that the optimal number of IT team members is

Table 6 Problems and solutions of scanning historical clothes—a case study of the turban

Object	Problem	Solution	Alternative
Turban (*salla*)	The turban's undoing while it was being taken out of the display case	The scan was carried out on a live model, i.e. on the head of a museum employee, which unfortunately led to (i) a significantly larger area of defects (5%) compared to the scan of the cloth, (ii) the impossibility of scanning both sides of the overhanging part of the turban due to adherence to the model's figure	Scanning on a specialised mannequin consisting only of a part of the head, placed on a tripod The use of such a solution leads to: (i) the overhanging part of the turban does not adhere to the model figure and can be scanned, (ii) the necessity to have such a device (in the display case the turban was presented on a makeshift wooden skeleton)

Table 7 Problems and solutions of scanning historical clothes—a case study of the low shoes

Object	Problem	Solution	Alternative
Low shoes (*kaushi*)	Obtaining a full image 3D model	Due to the relatively small size of the object, the scanning was performed on a specialised rotary table: (i) the use of a table with a rich pattern creating a texture covering its surface ensured the continuity of positioning of the obtained scanned points of the object, (ii) manual rotation of the table made it possible to carefully scan the object with the possibility of returning to previously scanned fragments, (iii) it was possible to freely turn the object in order to scan non-visible parts, (iv) the area of the lesions ranged from 0.5 to 1%, which was considered a very good result.	Scanning on a tripod on which the shoe was attached The use of such a solution leads to: (i) no need to turn the object over, the object is accessible from all sides, (ii) an uncomfortable position for the scanner operator and controlling the scanning process on the laptop monitor

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Table 8 Problems and solutions of scanning historical clothes—a case study of the high shoes

Object	Problem	Solution	Alternative
High shoes (*mahsi*)	Limpness of the upper part of the object	Due to the considerable height and flabbiness of the object, the scanning was performed on a tripod on which the object was placed. Thanks to this solution: (i) there was no obstruction of one side of the object by the collapse of the upper part, (ii) there was direct good access to all pages of the entire facility, (iii) the position of the scanner was not comfortable and required a lot of experience from the scanner operator—what counted was the so-called steady hand, (iv) the obtained area of cavities ranged from 3 to 5% and was smaller than the values obtained in the turban scanning	Scanning on a specialized rotating table with a reference surface The use of such a solution leads to: (i) the need to stiffen by stuffing the uppers to prevent it from collapsing, (ii) very gentle rotation of the table due to the height of the object and its instability in a standing position, (iii) troubles arising when moving the object to a lying position (sole scanning) due to the fact that the object's dimensions exceed the diameter of the table, (iv) the upper bends under its own weight when the interior of the object is improperly filled

3 people. The size of the support team may vary depending on the task being performed.

- Digitisation with a 3D SLS (in our case the Artec Eva model was used) is a relatively simple and fast process that can be performed in situ, without the need to create special working conditions for the IT team. The scanning process by a team of three of six elements of the outfit: dressing gown, turban (*salla*), two low shoes (*kaushi*) and two high shoes (*mahsi*), taking into account all the preparatory and finishing activities, took less than 1.5 h.

- 3D digitisation in the structured-light technology is a safe process for the scanned objects due to the fact that the technology used does not require any tags to be attached to vintage costumes, and the scanning process is low-energy and does not heat up the scanned objects. In addition, 3D SLS does not require interfering with the structure of digitised objects by sticking macros, which on the one hand can be dangerous for the surface of fabrics, and on the other hand, significantly increases the workload of preparing an outfit for digitisation and extends the post-processing time to make the final digital 3D model due to the necessity to do so.

- The applied 3D digitisation technology enables acquisition of evenly illuminated colour maps, thus simplifying the process of photorealistic materials creation for the purpose of physically based rendering. The creation of photographic documentation performed during the scanning process is primarily supplementary. The photos make it easier to assemble the acquired multiple point clouds into one 3D model, especially when the person submitting the model did not participate in the scanning process.

- Due to the high accuracy of the scanned objects, amounting up to 0.05 mm, the created 3D mesh Base Models are very large (from 20 MB for the Kaushi to 150 MB for the dressing gown). Such large graphic objects are perfect for archival purposes because they contain a lot of information about the surface area of scanned artefacts. The acquired models can be used to retrieve precise dimensions from the object at any time.

- The redundancy of the Base Models, understood as the available number of triangles reflecting the geometry of the surface, allows for their processing in order to obtain models suitable for presentation on websites and mobile devices. The activities carried out on these models show that their reduction by 70% or even 85% ensures both the sufficient quality of the 3D model and a reduction in their size sufficient for successful presentation on

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various platforms. The models have the respective sizes from about 4 MB for the Kaushi to 30 MB for the dressing gown.

Further work in the area of 3D scans using 3D scanners, specifically ones based on structural light, of historical clothes for the purpose of their documentation and dissemination will be carried out using the present methodology. It should confirm the correctness of the current approach and give directions for its modification.

Authors' contributions
Jerzy Montusiewicz conceived and designed the experiments, performed the experiments, analysed the data, authored or reviewed drafts of the paper, and approved the final draft. Marek Milosz conceived and designed the experiments, performed the experiments, analysed the data, authored or reviewed drafts of the paper, and approved the final draft. Jacek Kęsik performed the experiments, processed the scanned data, prepared figures and/or tables and approved the final design. Kamil Żyła processed the scanned data, prepared figures and/or tables, and approved the final draft.

Availability of data and materials
Processed point clouds of objects scanned into 3D artefacts are available on the website https://cs.pollub.pl/lab-3d/?lang=en. Data sets from 3D scanning are stored on the servers of the Laboratory of Inteligent Systems Programming and Computer 3D technology—'Lab 3D', and are not publicly available due to their size and data protection on the servers, but are available from Jerzy Montusiewicz upon a justified request.

Declaration

Competing interests
The authors declare there are no competing interests.

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