

## RESEARCH ARTICLE

# 3D scanning digital models for virtual museums

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**Summary**

A great number of virtual museums exhibit archaeological artefacts in an interactive form using 3D digital models to disseminate them to as many users as possible. Currently, 3D models obtained as a result of scanning museum objects have gained a great popularity. This technique allows to faithfully reproduce objects and to expose artefacts too delicate and precious to be presented in the real world. The aim of this paper is to create a virtual museum in the VR world using 3D models obtained by 3D scanning with structured light. The advantages of optimising mesh models for their use in virtual exhibitions are discussed. Unity and Unreal Engine, were used to create virtual museums in the VR world. Two twin test applications were prepared. This allowed to compare the performance of the developed applications (processor, graphics card and RAM load). A survey was also conducted among the users of the implemented virtual museum application. For immersion in the world of VR, a low-cost solution was used, involving the use of cheap VR frames, a smartphone and a computer. The frames together with the smartphone were used to display the image, while the entire rendering process was performed on the computer.

**KEYWORDS:**

3D scanning, 3D models, virtual reality, virtual museum

## 1 | INTRODUCTION

Due to the recent development of the reverse engineering technology the creation of increasingly realistic and accurate three-dimensional models has gained interest in many studies. In particular, 3D scanning allows the transformation of real objects and places into digital three-dimensional models<sup>1</sup>. It is used in many industrial fields, including construction, medicine, automotive and aviation.

3D scanning has also gained its application in the protection of broadly understood material cultural heritage. Current scanning technologies allow the creation of digital 3D models from very large objects such as buildings (laser technologies) to small archaeological artefacts (structured light technologies). In case of museums, such digital models are a tool that creates opportunities to present unique and complex collections of archaeological artefacts<sup>2</sup>. Due to the limited space of museums only selected artefacts can be exhibited. On the other hand, transferring the collections to the digital world allows for free and practically unlimited composition and arrangement, as it does not take up any physical space. Moreover, it is possible to create almost any number of parallel exhibitions. This solution also facilitates combining various exhibits, which is not always possible in the case of real exhibitions<sup>3,4</sup>.

Currently, several types of virtual museums may be specified. They can be part of a traditional museum as a supplement and make its offer more attractive, or exist as an independent unit functioning only in the digital world<sup>5,6</sup>. The first type of virtual museums are 3D Museums, which offer interactive 3D visualisations, allowing visitors to experience exhibitions in a more

realistic way than, for example, photo ones<sup>7,8</sup>. The second distinguished type concerns online museums, which usually consist of digital collections and resources<sup>9</sup>. They can be viewed or downloaded over the Internet. Next, virtual exhibitions applies to the third type of virtual museums. They can be used to view artefacts online, usually photos and videos. The last and the newest type are so-called Virtual Reality (VR) Museums. They allow visitors to both, enter the virtual world and experience exhibits in a way that is not possible in traditional museums<sup>10</sup>. In VR, one can explore the museum and interact with artefacts. VR museums provide a more authentic and interactive experience, allowing to better understand and remember information. The visitors can access exhibits that are difficult to see in the real world, such as artefacts from an ancient era, unique pieces of art or dangerous tools and machines. In VR museums, one can also browse exhibitions and see films, presentations and other multimedia materials, which allow for a deeper understanding of the history and culture<sup>11</sup>. Mixed forms of all types can also be found in many studies<sup>11,12</sup>.

Currently, due to the popularity and availability of smartphones, mobile applications are increasingly common, which allow users to download museum-related content to their devices, such as maps, guides and multimedia. George Lepouras and Costas Vassilakis<sup>13</sup> presented exemplary stages of designing and implementing a virtual museum. The authors emphasized the importance of these tips in creating computer displays to be the best in terms of quality and user comfort. Several aspects were specified such as selection of appropriate exhibits for the theme of a particular museum or the proper design of a digital exhibition. Moreover, the choice between a predefined path as well as creating a space in which the user can move freely were proposed.

A very important aspect is to choose the right methods of audio-visual presentations. It has to be customized to the type of exhibit, such as two- or three-dimensional photos, video or sound clips, models, text descriptions. Attention was also drawn to the careful adjustment of the type of interaction offered to the user. According to the exhibited objects, displaying, moving, rotating and even disassembling were taken into consideration. In addition, a significant impact of the adequate arrangement of virtual exhibits in a previously created three-dimensional computer space on the perception of the whole scene was noticed<sup>13</sup>. M. Skamantzari and others presented examples of virtual museums. The Unity graphics engine was stated to be one of the basic tools to create digital exhibitions<sup>14</sup>.

3D scanning is one of the reverse engineering technologies. It is focused on reproducing the scanned object as faithfully as possible. This means that the data collected by scanners in the form of a point cloud usually consists of a huge amount of information. These are useful data for creating accurate digital records. The tessellation grid models also consist of a large number of triangles (in the order of several hundred thousand to several million), which limits their potential use in digital exhibitions due to their complexity. Virtual museums available in a form of online applications require optimal 3D preparation of digital exhibits for "smooth" operation, i.e. minimising their size (triangle mesh, textures) while maintaining quality acceptable to recipients. This causes various difficulties at the stage of application development<sup>15,16</sup>. Kesik et al. characterised the available methods of scanning historical objects in their study. One of them is the use of a stationary device on which the item is placed and automatically scanned. According to the authors, this solution has also some disadvantages. It is not always possible to relocate the monument, because of its possible destruction. The above mentioned problem does not occur with handheld scanners operating in structured light technology. The need to move the exhibit is eliminated, thus minimising the risk of its damage<sup>17</sup>. Wachowiak et al. in their study showed how 3D scanners operate. Due to the appropriate lighting with structured light, which is arranged in patterns (e.g. stripes), the scanning device is able to analyse and translate the collected data into a three-dimensional model. The authors rose the problem of scanning some surfaces, e.g. reflective or absorbing light, or those that are transparent, and also indicated techniques that facilitate scanning in such cases. One of the mentioned possibilities was covering troublesome fragments with a matte spray<sup>18</sup>.

The protection of tangible cultural heritage is one of the important challenges facing humanity. Natural disasters and wars result in irreversible loss of many objects. One of the interesting and important cultural complexes in the world is the Silk Road, and its digitisation that allows for a better understanding and preservation of its heritage<sup>19</sup>. Due to 3D scanning, it is possible to archive and later, if necessary, restore the monuments of the Silk Road, such as buildings, milestones, tombs and temples. Virtual museums are an excellent tool for presenting digital models from the Silk Road area. Due to their interactivity and realism, virtual museums allow visitors to experience and understand this unique culture first hand. Through the use of new technologies such as virtual reality and augmented reality, visitors can visit and explore recreated models of the Silk Road directly. In addition, virtual museums also allow access to collections and information about the Silk Road to the general public, regardless of their geographical location. The availability of such online museums broadens the knowledge and understanding of the culture of the Silk Road, as well as to preserve this valuable part of history<sup>20</sup>.

This paper pursues the following objectives:

- development of digital 3D mesh models (through the use of 3D scanning technology) that are faithful copies of real museum objects;
- selection of technologies, devices, tools and software to develop a low-budget virtual museum operating properly in the VR environment;
- creation of a virtual museum using two graphic engines with objects interacting with the visitor in the VR world;
- performance tests of Unity and Unreal Engine graphics engines with the use of developed applications;
- conducting surveys of application users.

Moreover, in this study the concept of low-budget solution is presented in the opposite to expensive VR goggles. A smartphone, placed inside a frame, is used to display the VR world. The scenes in VR are rendered on a computer.

The rest of the paper is organised as follows: Section 2 give the guidelines for creating virtual museums, Section 3 describes objects and methods, Section 4 presents the virtual museums application, Section 5 shows the results, and finally Section 6 concludes the study and gives future research directions.

## 2 | GUIDELINES FOR CREATING VIRTUAL MUSEUMS

The development of photorealistic digital 3D models of all the necessary objects and the creation of a virtual museum in a VR environment requires a careful analysis of needs in terms of: technology, 3D design, software availability, their ability to effectively solve anticipated problems and the ability of devices to conduct a proper VR session. For virtual museums creating in virtual reality the following activities are performed:

1. Choosing the right VR Platform that the best suits your needs: there are various VR platforms such as Oculus Rift, HTC Vive, PlayStation VR, Samsung Gear VR, and Google Cardboard.
2. Development of realistic 3D models: they are a very important element while creating virtual museums. The models should look realistic and true to scale. There are various methods for creation realistic 3D models (3D scanning<sup>21</sup> and modeling using 3D graphics software and the Structure from Motion method<sup>22</sup>. You also need to consider details such as textures, shadows, lighting, and animations.
3. Use of interactive features: virtual museums in VR should be interactive. Visitors should be able to interact with the exhibits, such as dragging, rotating and zooming. You also need to allow visitors to move around the museum using a VR controller or body movement.
4. Use of audio and text descriptions: they are an important element of virtual museums in VR. You must provide exhibit descriptions so visitors can learn more about each exhibit.
5. Performance optimization: VR is hardware demanding and creating virtual museums in VR is computationally complex. You need to optimize your 3D models and other elements to ensure smoothness and performance across different VR platforms.
6. Testing: it is an important factor for creating virtual museums in VR. Models should be tested on various VR platforms and with different target groups to ensure that the virtual museum works well and provides the best experience. After testing, you need to correct errors and improve your models.

## 3 | OBJECT AND METHODS

One of the easiest and low-cost ways to explore virtual reality is to use a smartphone<sup>23</sup>. They are a popular solution in VR because most people already own them, so no additional investment in specialised equipment is needed. Only a cheap VR frame is enough (cost about 10-20 euros), which allows one to use a smartphone as a screen and a tool to interact with the virtual world. Placing the smartphone in the frame (goggles) allows to display the image of the application directly in front of one's eyes, and

the motion controllers let one interact with the virtual world<sup>24</sup>. However, the quality of the VR experience may be lower than that of PC-integrated systems such as the Oculus Rift or HTC Vive. Such solutions give the best results, but involve purchasing of expensive VR goggles. In this study, the authors propose an intermediate approach that allows the use of a smartphone and a computer. It significantly reduces costs for the user – apart from the phone and computer, which the user usually already possess. Only relatively cheap and easily available VR frame is needed. In this case, the phone is used as a display and all calculations and rendering are done on the computer. In this configuration, the phone is connected to the computer and displays the image rendered on the computer, but is not directly responsible for calculations and rendering. This approach allows for better image quality and a smoother visual experience than using only the phone and reduces the costs associated with the need to purchase expensive VR goggles.

### 3.1 | Tools for creating a virtual museum

For the preparation of digital 3D models, creation and testing of a virtual museum in the VR world, the following equipment was selected:

- Artec Eva structured light scanner for 3D model acquisition;
- Artec Studio Professional program for processing point clouds from the 3D scanning process;
- Blender program for designing a 3D model of the interior of the virtual museum and its equipment;
- Unity and Unreal Engine graphics engines for creating a virtual scene and embedding application logic;
- Visual Studio development environment for creating scripts in C# and Blueprint system, describing the application logic (including interaction methods and their results).

### 3.2 | Description of objects and their acquisition

The actual objects used to create the virtual museum are located at the Khoja Akhmet Yassawi Archaeological Museum of the International Kazakh-Turkish University Turkestan, Kazakhstan and the Scientific-Experimental Museum-Laboratory of the Samarkand State University in Uzbekistan. Three objects from the 10th to the 13th century were selected from each museum. Objects from southern Kazakhstan include a perfume vessel, a camel-shaped jug, and a fragment of an oil lamp. Objects from Afrasyab and Registan in Samarkand, Uzbekistan include jugs for storing wine and other beverages and a vessel for mercury.

The scanning of real museum objects was carried out in situ. A handheld 3D scanner using Eva structured light technology developed by Artec was used. This scanner does not require calibration or sticking positioning markers on the scanned object, which is very important when scanning historic museum artefacts. It is characterised by high measurement precision and high resolution. The basic parameters of the scanner are: 3D resolution up to 0.5 mm, data acquisition speed up to 2 million points/sec, texture resolution 1.3 MPx in colour, scanning distance 0.4-1 m.<sup>25,26</sup>. The objects were placed on a table in various positions. During scanning, the table was rotating and the position of the scanner relative to the object was changed at the same time. This allowed the acquisition of entire surfaces of scanned objects. The Artec Studio Profesional 15 program was used for data post-processing. This allowed for the transformation of the point cloud into a 3D mesh model with the applied texture. The Polygon Count Decimation reduction method was used. The PCD algorithm allows one to precisely control the degree of 3D model mesh reduction and the reduction of the number of vertices/triangles to a given value. That guaranteed their smooth presentation in the VM using the Level of Detail technique. This allowed the use of 3D models mesh with the number of triangles from several thousand (3000, 6000) to several hundred thousand. The digital 3D models were then exported to .obj files. It is a format storing the spatial model, i.e. geometry, and stores information about its texture (it maps the texture, which is impossible when saving to another format, e.g. .stl). Textures were exported to separate files in .jpg format.

### 3.3 | Creating a 3D scene model

The model of the virtual museum, i.e. rooms with its equipment (pedestals, lighting, floors, sconces, doors) was made in the Blender software. The appropriate arrangement of these elements, in particular pedestals, was made. In this case, one of the main aspect was to keep a lot of free space around the pedestal so that it can easily be approached from each side. In this

environment, the process of mapping textures to individual objects was also performed. Previously prepared 3D models with textures of museum artefacts were also imported and placed on pedestals. The final 3D model creating the scene of the virtual museum was saved in the .fbx format, which stores all information about the models, textures and settings and allows for import to graphic engines.

## 4 | VIRTUAL MUSEUM APPLICATIONS

### 4.1 | Creating

Two identical applications have been developed that allow to visit museum exhibits from the Silk Road in the world of virtual reality. These applications were made using two various graphics engines: Unity and Unreal Engine. Both software has been prepared in such a way that they are as similar as possible. This allowed to compare the received applications. Both engines use the same scene that was designed in Blender.

While creating the virtual museum application in the VR world, the following design assumptions were adopted: (i) the application is run on the user's desktop or laptop (all calculations and rendering), (ii) the smartphone with VR frames is only used to control camera and displaying the image from a laptop or computer (immersion in the VR world), (iii) communication between the computer or laptop and the smartphone takes place via Wi-Fi or a USB cable, (iv) the user must be able to: freely move around the stage, control camera and easily interacting with objects.

In the first stage, based on the prepared 3D model of the scene, a proof of concept was developed for the VR application in both Unity and Unreal Engine graphics engines. The prepared sketch had the implementation of the stereoscopic image rendering function, basic interaction control mechanisms, calibration of light sources on the stage and the method of shading objects (Fig. 1). Further work on the application required, above all, determining the scope of freedom of the participant in contact with the virtual scene. It is expressed by: the way the user's avatar moves within the scene, ways of interacting with elements of the environment, determining the results of interaction. For this purpose, a database of functions was developed, which was assigned by means of the script mechanism to the objects of the scene.

Moving around the stage is designed in two ways, with or without a controller. For the controller-free solution, the user should look at the icon in the centre of the screen horizontally and vertically below the centre of the screen to move. The icon moves horizontally behind the user, while vertically it stays in the same place. The user has to focus their eyes on the icon for 0.5 second, after which they can move in the direction they are looking. Moving continues as long as the user's eyes are focused on the icon. When the user looks elsewhere, it will stop. The user can interact with objects in the application. Objects of this type are highlighted when you look at it. On the other hand, interacting with an object takes place when the user is at an appropriate distance and focuses on it for a certain period of time. Then, depending on the assigned function defining the object's behaviour, appropriate events are performed, e.g. text is displayed, audio recording or animation is played.

Since the application is displayed on smartphones, the best way to control the camera is to use the gyroscope on the phone. To change the direction the camera is facing or its entire rotation, the user may change the position of the head. When the user rotates their head vertically, the camera also rotates vertically in the same direction as the user's head.

The Level of Detail (LOD) technique was used for optimization of performance on available hardware. The LOD is a tool allowing for improvement of the performance of a scene by loading a lower quality meshes in situations where the user does not notice the lack of details in models. It is based on the distance between the object and a camera (Unity) or percentage of screen surface occupied by model (Unreal Engine). Considering very high complexity of models in the best quality, adding the LOD was necessary to ensure smooth and correct performance of the application. The highest quality model of an artefact is only displayed when the user is standing as close as possible to the object.

### 4.2 | Testing

The developed applications were tested in terms of their efficiency, and pilot usability tests were carried out. Application performance tests for comparison purposes were performed on two different desktop computers and two laptops. In order to carry out the comparative analysis and to verify the efficiency four main criteria for examination were established:

- CPU load (measured as percentage);
- GPU load (measured as percentage);



**Figure 1** Virtual museum implemented in Unity game engine (left), Unreal Engine (right).

- RAM load (measured as MiB);
- FPS value - Frames Per Second.

Each measurement was performed in one minute and repeated ten times. In order for the tests to be comparable, the user covered the same route and kept the same order of viewing the exhibits. The parameters of the computers used in the research are listed in Table 1.

**Table 1** This is an example of Appendix table showing food requirements of army, navy and airforce.

Computer	Processor (CPU)	Graphic card (GPU)	RAM
PC 1	Ryzen 7 3700x, 3.60GHz	Radeon RX580	32GB
PC 2	Intel i5 4460, 3.20GHz	Radeon 270x	8GB
Laptop 1	Intel i5 8250U, 1.60GHz	NVIDIA GeForce 940MX	8GB
Laptop 2	Intel i5 7200U, 2.50GHz	NVIDIA GeForce 940MX	8GB

Pilot studies (surveys) were conducted on a group of 20 participants aged 20-22 (8 women and 12 men). The purpose of the research was to evaluate the developed applications. The authors wanted to verify the following research questions:

Q1: Would the quality of the rendered scene and all objects in it be satisfactory in terms of geometry and realistic appearance?

Q2: Would the effect of user immersion during the VR session be felt by them?

Users visited a museum made by means of the Unity graphics engine and then the Unreal Engine (Fig. 2). They could visit the museum and interact with objects to obtain detailed information about them.

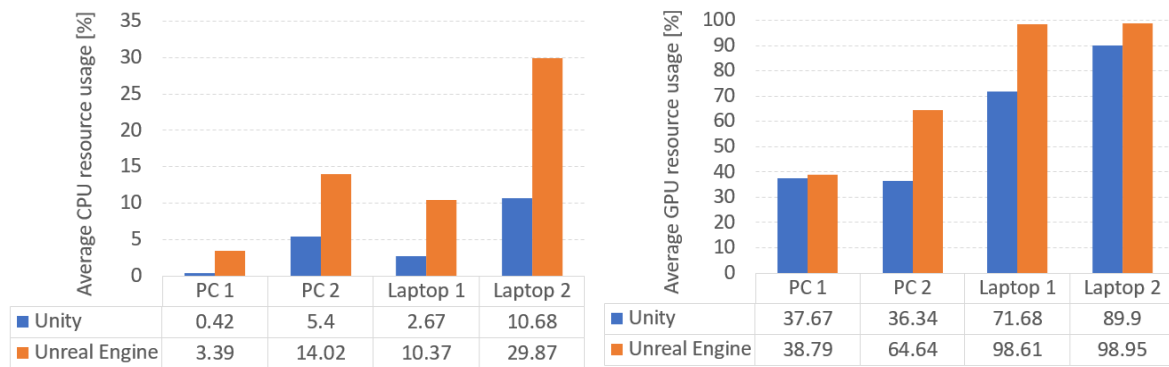
## 5 | RESULTS AND DISCUSSION

The implementation of the virtual museum application in the VR world, using 3D models with various details (number of triangles), allowed for the optimisation of scenes made in both the Unity and Unreal engines. The obtained results of the performance tests of the developed applications are presented in Fig. 3 – 4. The average CPU resource consumption for the tested applications on each of the hardware configurations is shown in Fig. 3. Lower CPU resource usage for desktop computers was observed for the PC 1 configuration, while in the group of laptops – for Laptop 1. It is interesting that the PC 2 device obtained in this category a worse result than the Laptop 1, despite having a better hardware specification. The probable cause of this phenomenon



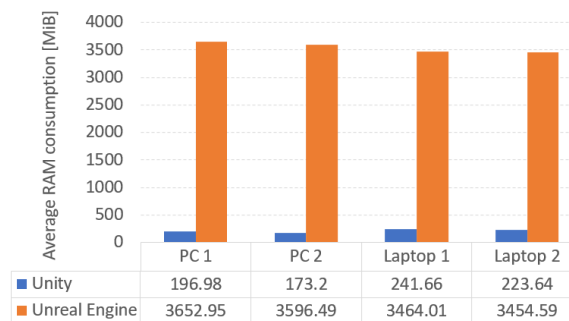
**Figure 2** Application tests with user participation.

may be partly related to the number of cores and threads available in each CPU. The PC 1 has the largest number of cores (8) and threads (16), which in this case results in the lowest CPU resource consumption. The PC 2 and the Laptop 1, on the other hand, have the same number of cores (4), but the Laptop 1 has more threads (8) compared to the PC 2 (4), which may explain the worse result of the PC 2. The lowest scores were obtained for the Laptop 2, which has the smallest number of cores among all tested configurations (2).



**Figure 3** Average CPU (left) and GPU (right) usage.

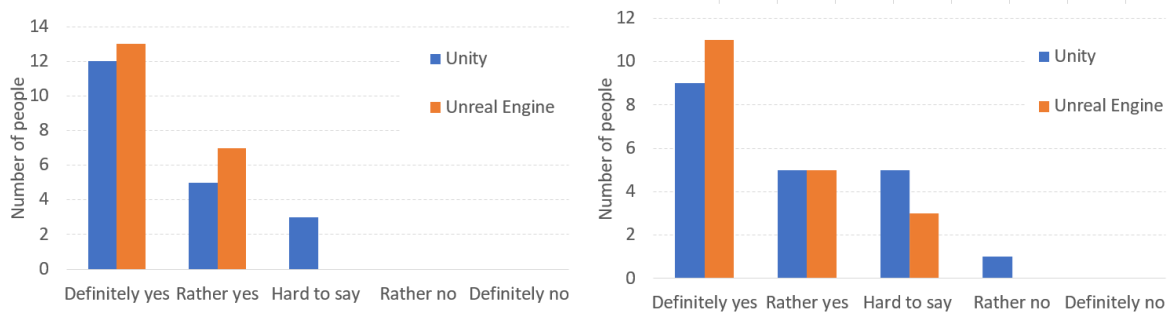
In Fig. 3 the average resource consumption of the graphics card is shown. In all analysed cases, the application developed in the Unity engine achieved better results than in Unreal Engine. The biggest difference can be observed for the PC 2 device, where Unity was almost 2 times more efficient. For both laptops, Unreal achieved a rounded 99% GPU load. Despite the fact that the Laptop 1 and Laptop 2 had the same graphics card, Unity scored slightly better for the second device in this category.



**Figure 4** Average RAM consumption.

In Fig. 4 the average RAM use of the tested applications is presented. There is a significant difference in the amount of RAM used. For the application developed in the Unity graphics engine, the consumption value did not exceed 250 MiB in any case, while in the case of Unreal Engine the value oscillated around 3500 MiB.

The applications were also tested in terms of the number of generated frames. In the case of the PC 1, applications developed in both Unity and Unreal Engine achieved a similar, very high result. For about 95% of the time tested, the PC 1 achieved values close to or equal to 60 FPS, which means a very smooth image. Similar results were also achieved in the PC 2 configuration. For each of the laptops, the Unity application was able to generate about 10 FPS more than in Unreal Engine. The least favourable result for Unreal Engine was obtained in the case of the Laptop 2 device and it was about 40 frames per second. This result is still satisfactory, allowing to achieve high image smoothness. The results show that less resources were used by the Unity engine, however, both engines provide high realism and smooth viewing.



**Figure 5** The results of the answers to question Q1 (left) and Q2 (right).

The results of the pilot studies obtained after answering the questions by the users of the application are presented in Fig. 5. To the question Q1: "Was the quality of the rendered scene and all objects in it satisfactory in terms of geometry and realistic appearance?" 100% of users responded positively about the application developed using the Unreal Engine. A similar situation took place for an application made in Unity, with the difference that three people answered neutrally "hard to say". Based on the obtained results, it can be concluded that the users felt at ease in the VR environment and were positively inclined to the sensory experience (immersion) of being in a different reality.

In Fig. 5 the answer to question Q2 "Was the effect of immersion and user interaction during the VR session noticeable?" is shown. In this case, users answered slightly differently than in Q1. There are more neutral answers: 5 and 3 respectively for the application made in Unity and Unreal Engine. For applications in Unity, there is one negative answer "rather not".

Creating a VR application is a complex process that requires developers to face and solve many problems. One of the biggest challenges is the configuration of the software environment and the subsequent development of the application. Many factors affect the correct application usage. Even a single fault can effectively inhibit the development of the project.

There are many problems at different levels of abstraction that can affect the performance of VR applications<sup>27</sup>. The process of creating a virtual museum in a VR world may be an example of it. While the application is launched on a computer or laptop and the image is sent to a smartphone, you can encounter many problems such as delays, image quality issues, lack of stable internet connectivity and device limitations.

The delay while transferring the image from the computer to the phone is one of the biggest problems. It can result in a lack of synchronization between the user's head movements and rendered images, which will affect the quality and smoothness of virtual reality. Another issue is image quality, which may be reduced during transfer, which may result in a blurry image or a delay in image rendering. The lack of a stable and fast Internet connection between the computer and the phone will also affect the image quality and slow down the image transfer. Mobile device limitations, such as processor or memory limitations, may also affect the quality and smoothness of the transmitted image. Some devices may also not be compatible with a given VR application or with a given video transfer technology. Transferring an image from a computer to a smartphone during virtual reality can also affect the heating of the phone. The main reason for this process is increased battery and CPU consumption during the processing and displaying the virtual reality. However, the use of mesh optimization methods can reduce memory



consumption and speed up the application, which will contribute to reducing device heating<sup>28</sup>. All of these factors present challenges for developers who need to find ways to address them effectively.

## 6 | CONCLUSIONS AND FUTURE WORK

Based on the study carried out, the following conclusions can be drawn:

- the selection of digitisation technologies and tools for virtual reality together with the software used for 3D scanning, post-processing, modelling and creating a virtual museum turned out to be appropriate and allowed to effectively solve all emerging problems;
- the use of digital silk road models from 3D scanning after their optimisation allowed for the development of a virtual museum in virtual reality technology;
- the implementation of interactive tools allowed for an interesting and attractive presentation of the collected data and information (which increases the attention and interest of users);
- the applied technological solutions enable easy and quick updating and supplementing of information, which will allow for constant development of the virtual museum;
- performance test results showed a lower resource consumption of the Unity engine, while both engines provide a smooth visual experience while visiting a virtual museum;
- users confirmed the satisfactory quality of the rendered scene in terms of geometry and realistic appearance as well as the feeling of immersion and interaction during sightseeing.

In addition to the above conclusions, the use of digital Silk Road models to create virtual museums has several other benefits, including:

- enables a more interactive and engaging experience for visitors compared to traditional museums;
- allows to save costs and resources that are needed to maintain a traditional museum;
- enables quick and easy updating of information and collections;
- strengthens the knowledge and understanding of the Silk Road through interactive and educational elements.;
- provides access to Silk Road information for people with different needs and limitations, such as people with disabilities.

Overall, these findings suggest that the selected technologies and software have been successful in delivering the project and creating an effective and attractive virtual museum. The use of digital models of the Silk Road to create virtual museums is a promising direction in the field of protection and presentation of cultural heritage. It is important to continue researching and developing digital opportunities to ensure the best experience and accessibility for visitors.

### Financial disclosure

None reported.

### Conflict of interest

The authors declare no potential conflict of interests.

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