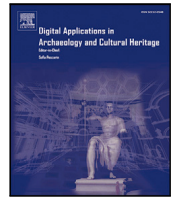


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Virtual reconstruction of the Red Room exhibition

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ABSTRACT

Museums increasingly use interactive installations to enhance exhibitions with additional content. Virtual reality can give the visitor access to remote places and bring the past back to life. This is especially interesting when artifacts cannot be brought back since they were sold or otherwise lost. In this project, we have partially reconstructed the Giech's family exhibition in the Red Room of Thurnau Castle. The exhibition ended when the family had to sell the exhibits in the 19th century because of financial problems. The goal of the project is to fully reconstruct the part of the exhibition that was shown in the Red Room based on a painting and the list of artifacts. While museums explain exhibits using information boards, the visitor of the Giech's family exhibition would have been guided by the earl himself. Therefore, we used virtual reality interaction techniques to make the exhibition more immersive and accessible.

1. Introduction

How might it have felt for a person to walk through the collections of the Counts of Giech at Thurnau Castle (Upper Franconia, Germany) in the 19th century, a museum that no longer exists? That was the initial question that led to our project. Since the Franconian noble family of Giech moved into the castle in 1564, they continued to collect all kinds of art (paintings, tapestries, furniture, porcelain, etc.), military items, and many books. Those collections were presented in 1857, when Count Carl of Giech decided to open the castle to the public (Fig. 2). It was just the right time because the family had lost its political power and the museum could at least commemorate the important role the Counts of Giech used to play. In the so-called Red Room, located in the bower, the exhibits reflected the family's relationships with other nobles near and far. This is the room that we wanted to virtually renovate and open for visitors to experience. Today, the collections are no longer located in the castle, some of the former exhibits have even been sold, and the locations of these objects were or are uncertain. Therefore, a group of students started to search for all the exhibits that were displayed in the Red Room. We analyzed the handwritten museum inventory from 1863 and consulted additional sources and literature, including an 1863 painted picture of the Red Room. We have located many, but not yet all of the objects that used to be shown. These include paintings, tapestries, shields, a cradle, display cases with smaller exhibits, and much more. We have gotten in contact with the current owners of the objects and asked for permission to take photographs of the objects, which would make it possible to recreate virtual 3d models of the objects.

While the initial goal of the project was only to digitize the exhibits and show them in the virtual room together with textual information, it quickly became clear that this would not resemble the experience of a visitor in the 19th century. We therefore decided to present the room using a virtual reality (VR) head-mounted display (HMD) instead of a simple computer screen. In addition, the textual information was replaced by audio descriptions of the exhibits similar to audio guides found in most museums today. In contrast to audio guides on special devices or smartphones however, VR allows a much more natural interaction by simply touching the object to start playing the audio information instead of pressing buttons, typing numbers or scanning QR codes.

1.1. Contributions

The main contribution of this paper is an immersive and easily accessible virtual exhibition that was designed to be as intuitive and immersive as possible. We achieved this by presenting the whole information as short audio explanations that are triggered by touching the exhibits with the hand or the VR controller. In developing the virtual exhibition, we addressed four research questions on ease of use and accessibility. The most important one is the design goal of our application, if a virtual reconstruction can convey the experience of the lost exhibition (Q1). To address this, we have accompanied the first two public virtual exhibitions with interviews of the visitors. During development, we used two smaller studies to answer several design

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Fig. 1. From left to right: painting of the Red Room showing some of the exhibits of Carl of Giech family collection (Heinrich Grünwald, 1863), photograph of the room as it looks today, partial reconstruction of the exhibition with the already digitized exhibits.

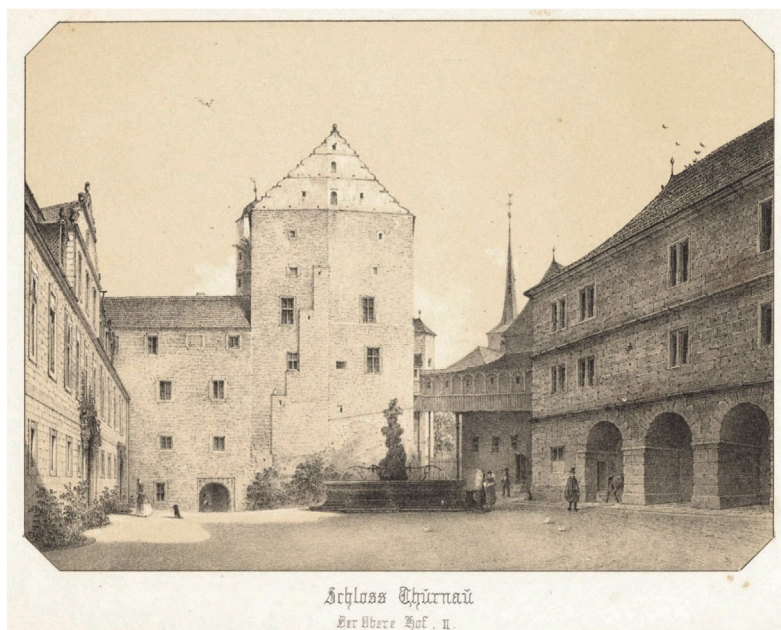


Fig. 2. Copper engraving showing the upper courtyard of Thurnau Castle with the bower house (Carl August Lebscheé, 1851).

decisions. The questions addressed within these were if written or audio explanations and if pointing or touching are more immersive (Q2 and Q3). In a first public study, we also collected information about what instructions participants without prior VR experience require to use the system (Q4).

To visually fully integrate the exhibits into the room, we use global illumination effects like shadows and inter-reflections. While previous systems already estimated the reflectance properties of the objects from photographs, global illuminations also require the estimation of light sources in the room. Therefore, we simultaneously estimate the light source intensity and reflectance properties. The method requires only little manual input from the modeler to produce highly accurate results. For rendering, we use a combination of pre-computed global illumination with light and reflectance probes for dynamic and specular objects.

2. Related work

The definition of virtual museums and virtual exhibitions has changed significantly over the last decades (Schweibenz, 2019). While originally any digital collection (e.g. The Virtual Museum by Apple (Apple Computer, 1992)) or collections of digital art (e.g. the Museum of Computer Art (Archer, 1993)) were referred to as virtual museums, today the term usually implies some kind of interaction with digital and often 3d content. The most interesting applications are where the virtual exhibition can show information that would be very difficult to

convey in the real world. This includes virtual restorations (Pietroni and Ferdani, 2021) that often present different alternatives or overlay additional information, e.g. the degree of certainty. Other virtual exhibitions add game-like interactions that are especially designed for younger visitors (The Hague, 2024). Immersive applications that populate virtual restorations of archaeological sites with virtual humans to show their daily life (Sierra et al., 2017).

Due to the comparably low cost of photogrammetric 3d reconstruction, it is often used to digitize cultural heritage artifacts (Morita and Bilmes, 2018b). One of its advantages over laser range scanning is that the images also contain valuable information about the appearance in addition to the geometry of the object and it has therefore become the standard technique for the documentation of 3d objects in cultural heritage (Remondino and Stylianidis, 2016). With sufficient image quality and quantity, photogrammetry can produce 3d models with the same accuracy as expensive laser scanners (Morita and Bilmes, 2018a). In addition to manually capturing images using a digital camera, there are also approaches using specialized optics for very small objects (Yanagi and Chikatsu, 2010). Transporting the artifacts is often not possible and therefore mobile 3d scanning systems are used in these cases (Ramm et al., 2022). As museums often own many more objects than they display in exhibitions, even high-throughput systems for mass 3d scanning have been developed (Santos et al., 2014).

Recently, interactive gaming technology came into attention for cultural heritage applications. In the Etruscanning project (Pietroni and Adami, 2014), visitors stand in front of a screen and interact

with gestures to move through the site and access audio information about artifacts. With the introduction of virtual reality hardware in the consumer market, virtual exhibitions became much more immersive. The digitization pipeline is extended by building an interactive environment (Fernández-Palacios et al., 2017), typically using a game engine and interaction techniques developed for games. Although early systems already used a sophisticated 3d reconstruction pipeline, they only allowed the visitor to move through the exhibition or archaeological site. Additional information about the exhibits was presented on text badges as in real museums (Loaiza Carvajal et al., 2020). Compared to VR games, it quickly became clear that much more interactivity would be possible. Following the line of interactive narration in computer games, complex interactions can be implemented for interactive storytelling. Guiding the visitor through the “story” is difficult and therefore 2d graphical user interfaces (GUIs) and text overlays are often integrated into the virtual environment (Besoin et al., 2021). Although the feedback of the visitors was positive in general, text overlays and 2d GUIs are known to reduce or break immersion.

3. Overall workflow

The project started with building a detailed photogrammetric reconstruction of the Red Room where some of the most impressive objects were shown. Then, the historical research to determine which objects were displayed and where they are today started. After locating the first few of the objects and getting permission from the owners to take photographs of them, we could start building 3d reconstructions of these as well. The virtual exhibition was composed using a 3d game engine with the goal of making the interactions as intuitive as possible and additional information on the exhibits is conveyed with audio explanations. The location and digitization of the exhibits were carried out by master students in history during a practical course on digitization in historical research that was taken by about 10 students on average. Over several semesters, more and more exhibits were found and added to the virtual exhibition.

4. Historical research

In a first step, the students went through the relevant sources of the Giech Archive. This family archive was transferred to the Bamberg State Archive in 2003, and all of the files can be used for historical research. It includes all kinds of historical material that contains information about the state administration and also about the personal belongings of the Giech family. The most important source is a museum inventory, written by an official in 1863 (Fig. 3). It is actually a compilation of all the objects on display in the castle for each of the individual rooms. The description of the Red Room tells us which exhibits were shown there, but not where exactly these exhibits have been located.

Fortunately, we have another source, a painting of the Red Room by Heinrich Grünwald from 1863, which gives us at least an insight into a part of the room. We were not (yet) successful in finding all of the objects of the Red Room according to the inventory. Some of the objects are still owned by the Hiller of Gaertringen family, the successors of the Giech family. The family gave us permission to digitize the objects. Others were sold over time. The last Count of Giech, Franz Friedrich Carl Lothar, for example, sold two of the so-called ‘Khevenhueller’-tapestries to an antique store in Berlin in 1925. Some years later, William Randolph Hearst, the famous American newspaper publisher, bought the tapestries and brought them to the USA. In the 1970’s they appeared again in a Sotheby’s auction catalog, but the current owner is unknown. We used the images of the tapestries from the catalog as input images for our project.

5. Artifact and room digitization

We digitized both the room and the objects using a photogrammetric reconstruction pipeline. The photographs were taken with a Canon EOS 5D Mark III camera at a resolution of 22 megapixels in raw format. In the Red Room we took about 450 images and for the objects between 50 and 200 depending on geometric complexity. Unfortunately, we could only get single pictures from three of the objects, due to the aforementioned reasons. For those, we could only use the images as textures on a simple proxy geometry. Since all of them are mostly planar, we used a rectangle and the alpha channel of the texture to encode the shape.

5.1. 3D reconstruction

For the photogrammetric reconstruction, we used Agisoft Metashape (Agisoft, 2024) which outputs a textured triangle mesh and is one of the standard tools used for the 3d reconstruction of objects and whole sites in Archaeology and Cultural Heritage. The software also contains an unlighting filter to compute albedo textures that we used when digitizing the exhibits. Unfortunately, the results of the unlighting were not satisfactory for the 3d model of the Red Room due to the diffuse light shining through the seven windows. Therefore, we developed an algorithm specifically tailored to this problem (see Section 6.1).

5.2. Mesh processing

After 3d reconstruction, we have used Meshlab (Cignoni et al., 2008) to manually remove any parts that did not belong to the model. This was mainly the ground on which the objects were standing. We then simplified the models to reduce the number of triangles for real-time rendering in the VR environment.

6. Virtual environment

We employ the Unity 3D game engine (Unity Technologies, 2019) (version 2019.4) to implement the rendering and interaction system, because it has build-in support for VR and different real-time global illumination algorithms. Using a game engine also has the advantage that it includes all dependent libraries and significantly reduces the development time. The engine is based on so-called scenes that contain both the objects as well as lights and other non-visual entities like audio sources and interaction mechanisms. For VR applications, the user is represented as a tracked camera and audio listener for the HMD together with hand objects that are usually controlled with VR-controllers attached to the users hands.

Since game engines usually support all different types of VR devices, our virtual exhibition is not bound to a specific VR system. We used two different systems for testing, the HTC Vive (HTC, 2016) and the Valve Index (Valve Software, 2020). Both are based on outside-in tracking within a so-called play area of up to about 20 m² in which the user can freely move around. While these systems use controllers that are held or strapped to the hand, it would also be possible to use systems where the hand poses are reconstructed from cameras attached to the HMD.

6.1. Scene setup

The Red Room was captured during an overcast day in late summer to reduce highlights in the images. Nevertheless, the photographs still contain a combination of the surface reflectance properties and direct and indirect lighting. These are also present in the textures of the reconstructed model (see Fig. 4 left) and could not be automatically split during reconstruction because of the complex lighting situation. Extracting light sources and computing albedo textures is an ill-posed problem that either needs some assumptions or additional data. We therefore chose to require a minimal amount of manual input from

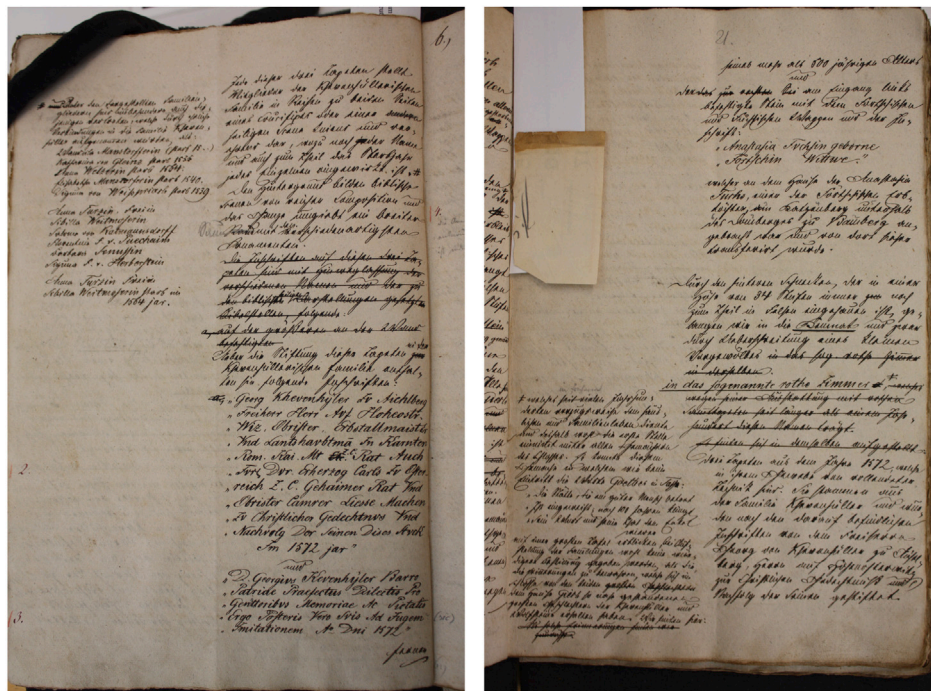


Fig. 3. Two pages of the collection inventory describing the objects shown in the Red Room (1863).

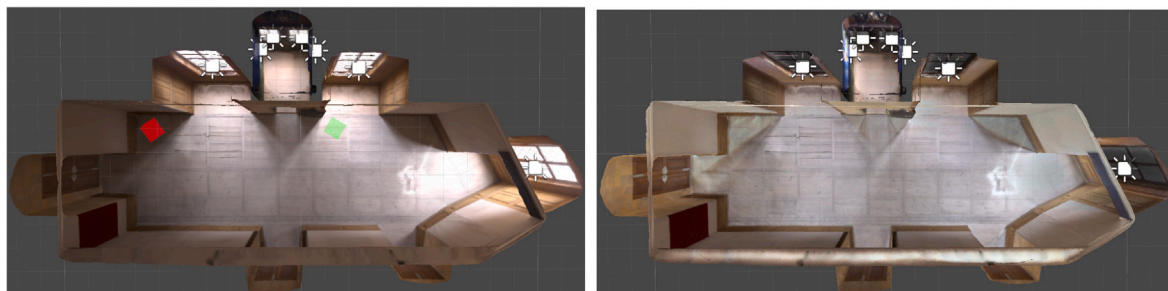


Fig. 4. Left: Top view of the room showing the 7 area light sources together with the directly lit (green) and shadowed (red) region used for optimization. Right: Model with computed albedo textures rendered without lighting.

the modeler. As setting a threshold to automatically extract the light sources did not work due to the reflections on the floor that were of similar brightness as the windows, the size and positions of the 7 area light sources were manually defined. To estimate their brightness, two small regions in texture space were defined by clicking on points of the model containing the same material and visually checking if the regions do not cross a texture seam. One of these regions is directly lit by the sunlight shining through a window and the other one only receives indirect light.

After defining the light source geometry and selecting the two regions R_{lit} and R_{unlit} , we use Unity’s build-in pre-computed global illumination algorithm to estimate the surface albedo. We start with the textures of the reconstructed model as initial estimate and iteratively optimize the light intensity L and the albedo texture T_{albedo} using algorithm 1. In addition to the lit texture T_{lit} we also need the total light source area as input since the brightness of area light sources in Unity is defined per square meter.

Starting with the lit texture as initial estimate of the albedo texture, we first estimate L . If L is estimated correctly, the lit and unlit regions should have the same average albedo. If not, then we can use the difference to update L by simply taking the difference and scaling it with a damping factor λ to compute an update step ΔL . Initially, we set λ as reciprocal of the light source area, but if the absolute value of ΔL increases, we reduce the step size to prevent divergence. The final

albedo textures are shown in Fig. 4 (right) by rendering the model with the albedo texture and lighting switched off. Some artifacts are visible at the shadow boundaries because of slight inaccuracies of the light source geometry, but they are not visible when rendering the final lit scene.

6.2. Interaction system

While walking through the scene using the tracking information of the VR system is natural and straightforward, we had to decide how to interact with the exhibits and how to present additional information about them. During the first tests with an early non-VR application, it quickly became clear that audio information was preferred over text overlays by all participants. While for the desktop system, clicking on an object was the most intuitive interaction metaphor, the direct translation to VR by pointing on a object and pressing a trigger was not ideal. In the historical exhibition, a visitor would probably only point to or even touch an object and ask what it is. As we did not want to integrate voice control, we compared pointing and trigger pressing with simply touching the objects with the hand. All participants in this test clearly preferred touching as more immersive, although they had to move more to actually reach the exhibits, and one participant said that pointing was more comfortable. Whenever the visitor’s hand collides



Fig. 5. First three images from the left: Visitor touching different exhibits to start the audio explanation. Right: Teleport metaphor used to cover larger distances than the play area.

Data: T_{lit} , R_{lit} , R_{unlit} , A_{lights}

Result: T_{albedo} , L

$L \leftarrow 0$

$T_{albedo} \leftarrow T_{lit}$

$\lambda \leftarrow \frac{1}{A_{lights}}$

while not converged do

$\Delta L = \lambda (T_{albedo}(R_{lit}) - T_{albedo}(R_{unlit}))$ // compute step
from average albedo in both regions

if $|\Delta L|$ has increased **then**

$\lambda \leftarrow 0.5\lambda$ // reduce step
size

else

$L \leftarrow L + \Delta L$ // update
estimated light source intensity

compute T_{irr} using L and T_{albedo} // compute
irradiance texture T_{irr}

$T_{albedo} \leftarrow \frac{T_{lit}}{T_{irr}}$ // pixel-wise
update of albedo texture

end

end

Algorithm 1: Iterative computation of light source intensity and albedo texture.

with an exhibit and its audio description is not yet playing, we start playback and stop any other currently running audio. In addition, the object is highlighted with a yellow outline as visual feedback (see the first three images in Fig. 5).

The only non-natural interaction that is still required is teleportation because the Red Room is significantly larger than the play area (see Fig. 5, right). Fortunately, most visitors already knew the teleportation metaphor from other VR applications and the other quickly understood the concept when it was explained and shown to them during the short audio introduction. The explanation was added after evaluating the observations made in the first public exhibition. After general information about the room and the exhibition, the controllers vibrate and the button used for teleportation is highlighted on each of them. The visitor is asked to press it to initiate the first teleportation, then the controllers vanish and only the virtual hands are shown.

In addition to the VR application, the exhibition can also be “visited” on a normal desktop computer or laptop using the mouse to interact with the exhibits and the keyboard for movement (see Fig. 6). This allows a wider dissemination of the virtual exhibition but cannot replace the VR experience because of the lower immersion.

6.3. Adding the exhibits

After digitizing the exhibits, they were placed according to the painting (Fig. 1) or estimated from the order in the collection inventory. Then we pre-compute the global illumination and store them as pre-computed irradiance textures. For specular surfaces as the glass cover of

the display cabinet and for dynamic objects, we additionally computed 12 light and reflectance probes distributed in the room for real-time global illumination effects. The sound recordings are attached to the objects as sound sources so that the visitor can easily recognize the currently described object. The introduction is analogously added to the room so that the sound originates from the center of the scene.

Finally, collider meshes to detect collisions between hands and objects are computed. Both convex and non-convex colliders can be used in Unity. As we do not require exact collisions, we used the convex colliders whenever possible and only used the non-convex ones for larger objects like the chairs and the display cabinet. To allow touching the objects inside the cabinet, we did not include the glass cover as collider, but only the corpus of the cabinet. In addition, we assign a higher priority to smaller objects so that their audio is not stopped when the visitor accidentally touches the cabinet.

When adding the small exhibits inside the cabinet, we noticed severe performance issues when using non-convex colliders. We therefore resorted to convex ones for those which solved the performance problem and made the objects slightly easier to touch. Fortunately, this did not occur for any of the larger objects.

7. Results and discussion

Already during development, we based our main design decisions on two small studies with 5 participants (2 male, 3 female) with an age between 13 and 47. The first study was carried out with the desktop application and addressed the question if visitors prefer audio or written information about the exhibits (Q2). All of them preferred the audio explanations which is also supported by the trend of real museums to increasingly use audio guides. The two participants who had some VR experience also suggested that a VR application would be more suitable.

In a second design study with the same participants, we presented the VR application where interaction was either by pointing towards the objects and pressing the trigger on the VR controller or by “touching” the exhibits, i.e. a collision of the virtual hand with the object (Q3). All participants chose touching to be more immersive since pressing the trigger reminded them that they were using a device for interaction. One participant said that pointing was more convenient since it requires less walking around, but nevertheless agreed that touching is more immersive.

In a first public presentation, we addressed the final design decision, which information should be given to the visitors in the introduction (Q4). About 15 participants (approximately half male/female) with mostly no experience in VR applications were equipped with the VR headset and controllers and instructed to move around the virtual exhibition and touch the objects for more information on them. Their questions and our answers were written down and we extracted the required instructions from them. In addition to information on how to wear the HMD and how to adjust it, 11 participants had questions about how to move in the virtual environment, while two participants also asked how to use the controllers. In addition to a two-page excerpt



Fig. 6. Desktop version of the virtual exhibition with mouse and keyboard control.

from the VR hardware manual on how to put on the HMD and handling of the controllers, we therefore added an explanation of the teleport function in the VR application.

To answer the main research question, whether a virtual reconstruction can convey the experience of the lost exhibition (Q1), we conducted a total of about 20 unstructured interviews after two virtual exhibitions at Thurnau castle. The participants (one third female and two thirds male) were between 25 and 60 years old. We asked if they could get an impression how it would have been to visit the lost exhibition. All visitors of the virtual Red Room were very impressed by the extremely realistic environment and said they could imagine how it would have been to visit the real exhibition. During the conference in which the first virtual exhibition took place, the participants had the opportunity to visit the real Red Room in the castle afterwards. “The illusion is almost perfect, I am missing the objects in the real Red Room”, one of the participant said.

We were also able to validate accessibility during the two exhibitions in Thurnau. The only observed issue was with a visitor with a wheelchair and with a few other people who could not reach some of the exhibits. This could be solved by either shrinking the room or by floating above ground. Both are not ideal, as the first alters the impression of the room and the second can cause VR sickness. Instead, we re-integrated the possibility to point towards the object and press the trigger to allow interacting with unreachable objects.

The overall development time for setting up the virtual room and adding the first few artifacts was about 40 h, but this included implementing all the different interaction variants. The total hardware and software cost for the digital camera, the photogrammetry software, the VR system and the PC was about 5000\$. Once the system was set up, adding an additional exhibit took about 3 to 5 h for taking the images, reconstructing the model, recording the voice information and adding everything to the virtual room.

The digitized Red Room opens up many new possibilities. First of all, and that was our main concern, we can visit the exhibition and perceive almost the same impressions that a visitor of Castle Thurnau might have had wandering around the Red Room in the 19th century. Although the exhibits are not in the actual room and we do not even know where some of them are right now, the digitized room turns back the wheel of history over 160 years. This also gives us an impression of exhibition concepts and object arrangements during that period of time that can be discussed widely and be compared to current exhibition concepts.

For the current castle owners, a public foundation, the virtual exhibition allows to show the history of the castle and its original owners. But it also allows the owners of the collection to show the exhibits without having to bring them to a museum. The experience of the digitized Red Room is also generating great interest in the real castle museum, which no longer exists. “Maybe we can bring back some of the objects into the castle”, suggested Hans Georg Hiller von Gaertringen, one of the current owners of the former Giech collections. The digitized Red Room and the impression how the room could look

like brought the foundation owning the castle and the owners of the collection a little bit closer together. In late 2024 two small rooms of the castle housed parts of the collections, which could be visited on guided tours.

CRediT authorship contribution statement

Michael Guthe: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Marcus Mühlhnikel:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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