VR System for the Restoration of Broken Cultural Artifacts on the Example of a Funerary Monument

Patrick Saalfeld*
University of Magdeburg, Department of Simulation and Graphics, Germany

Claudia Böttcher
Cathedral Support Association Magdeburg, Germany

Fabian Klink
University of Magdeburg, Department of Mechanical Engineering, Germany

Bernhard Preim
University of Magdeburg, Department of Simulation and Graphics, Germany

Figure 1: Our VR system for the reconstruction of cultural artifacts. The restorer (left) can pick fragments out of a large wall consisting out of all available fragments. The photographs in the gallery (right) serve as a template to assist in the assembly process.

Abstract

We present a VR system that supports the restoration of broken cultural artifacts. As a case study, we demonstrate this approach for the restoration of a funerary monument. Among the challenges of this monument are a large number of 415 fragments, an unknown amount belongs to another artifact, missing pieces prevent a full reconstruction and the preserved fragments vary strongly in size.

Our VR system supports the workflow of digital restoration by offering a configurable self-arranging fragment wall. It supports the user to organize all fragments in an overview representation and to identify relevant fragments quickly. For assembly, we implemented a jigsaw approach comprising two sets of manipulation techniques that allow the user to roughly align fragments first in sub-puzzles and precisely assemble them in a second step.

The iterative development and assembling process was accompanied by a professional restorer. We report about the insights we gained from this process and how we optimized the VR system according to her requirements and feedback. Within 14 sessions that took 21 hours, the virtual reconstruction was finalized.

Index Terms: Human-centered computing—Human computer interaction (HCI); Human-centered computing—Interaction design Human-centered computing—Visualization Applied computing—Arts and humanities Applied computing—Digital libraries and archives

1 Introduction

Cultural heritage plays a critical role in preserving the legacy of past societies and transferring past knowledge and traditions to future societies [49]. Cultural artifacts are often damaged and only partially preserved due to natural influences such as deterioration [12] or artificial factors such as human-caused destruction. Due to advancements in 3D scanning technologies, an increasing number of these artifacts is digitized and reassembled in the process of digital restoration, which complements traditional techniques of restoration [32, 34, 38, 39]. Digital restoration allows to test assembly configurations that would not be possible in physical attempts. Also, the danger of further damaging fragments during the assembly process can be avoided. Further, VR systems can offer quicker and less erroneous restorations compared to a desktop system [9, 23].

In this work, an interactive VR system for the digital reconstruction of a cultural artifact is presented. As a case study, we chose the reconstruction of a funerary monument that was destroyed during World War II. As it is for many cultural artifacts that were destroyed during war, the remaining pieces are abraded and incomplete. Further challenges of this digital restoration task comprise:

- The large amount of 415 fragments.
- The variance in the relative size of the fragments (varying by factor 36 from 0.07 m to 2.54 m).
- A previously unknown number of fragments belonged to another funerary monument that was built by the same sculptor in a similar style. After the destruction of both funerary monuments the fragments were stored together.
- The damaged remains of the funerary monument are still mounted on a wall. Using a traditional approach with testing of several possible pieces is not easily possible, as many fragments are heavy and bulky.

The development and reconstruction process was accompanied by a professional restorer (co-author of this paper). Within 14 sessions and 21 hours of virtual reconstruction, the restorer and a computer scientist investigated all fragments and identified fitting pieces. During these sessions, the funerary monument was restored incrementally. Simultaneously, the VR system was optimized according to the restorer's requirements and feedback. From 415 fragments, 17 % were excluded as they belong to the other funerary monument. Of the remaining 341 fragments, 182 (53 %) could be assembled resulting in a finished virtual reconstruction of the funerary monument, which will now be reconstructed physically based on our results.

Our main contribution is a VR system that supports the workflow of digital restoration including:

*e-mail: patrick@isg.cs.uni-magdeburg.de

- A configurable self-arranging fragment wall to organize all fragments in an overview representation that groups or clusters fragments according to user-chosen properties.

- Manipulation techniques for two steps of assembling: (1) quick alignment of corresponding fragments and (2) precise assembling of sub-puzzles. These manipulations techniques are chosen based on an in-depth discussion of available techniques.

2 Background and Related Work

In the following, we describe the traditional restoration process and then discuss related work on *virtual heritage*, a term coined by Roussou [42], to summarize the use of virtual techniques for preserving, reconstructing, and disseminating cultural heritage.

2.1 Traditional Restoration Process

As a first step, an inventory of all fragments is created that contains images and measurements for each piece. Furthermore, descriptions of the material, degree of degradation, type and possible connections are added. After that, a documentation of the original state is collected, e.g. photos and descriptions. Images are used to mark where fragments could be positioned and where pieces are missing. The final step of reconstruction starts with solving *sub-puzzles*, where fragments are arranged on a flat surface, edges are investigated and fitting pieces are glued together. Here, a group of restorers, stonemasons and stone carvers work together. This process is time-consuming, because fragments can be heavy and may have to be fixated to other pieces. Also, fragments can suffer secondary damage from the physical contact or force applied during fixation.

2.2 Virtual Heritage

Most of the work related to the use of virtual heritage aims at the broad public, e.g., visitors who may interact with each other [3, 52]. Essential research aspects are how to keep a high and constant frame rate without sacrificing geometric detail, how to navigate in virtual reconstructions and educational aspects, such as designing appropriate narratives to convey ancient culture in context. Immersive and interactive environments were already introduced by Gaitatzes et al. [15]. Their examples are the ancient city of Miletus and the reconstruction of the Temple of Zeus. Often a walkable virtual environment is created and appropriate interaction techniques are designed to explore the virtual environment. While Gaitatzes et al. [15] argue for CAVE-based VR solutions where the user is still aware of other visitors, Webel et al. [52] employ VR headsets like we do in our paper. In the CAVE-based system, users employ hand-held devices for interaction and navigation beyond the walkable area.

VR-based solutions primarily aim at increasing the number of people that have access to a cultural heritage site and to improve the quality of the experience [4]. Selmanović et al. argue [44] that the appeal of these environments can be increased by interweaving them with digital storytelling, allowing the consumer to experience a storied narrative inside a virtual 3D reconstruction.

The second branch of virtual heritage research aims at experts, e.g., archaeologists, historians and scientists [15]. Digital 3D acquisition technologies, such as remote sensing and laser-range scanning, are widely used for documenting archaeological sites, and as a starting point for reconstructing artifacts [17]. Raw point cloud data has to be converted into accurate 3D meshes minimizing the effects of misleading artifacts from the acquisition process. The 3D models need to be enriched with further semantic information, e.g. w.r.t. names or categories of parts. Building information modeling systems are adapted to cultural heritage contexts [27]. Guidi et al. use the term *reality-based representations* to refer to the digital acquisition. 3D models in these settings serve to support the reasoning process of archaeologists. Such virtual reconstructions involve elements based on excavations, which are often reliable sources of information, but also elements that were, e.g. added based on assumptions about architectural styles at a time. As an example, the Kaiserpfalz in Magdeburg, Germany was reconstructed in a collaboration between historians and computer scientists [47]. A major challenge was to develop visualization techniques that convey the uncertainty involved in parts of the reconstruction. They made the important point that photorealistic rendering is not appropriate to convey uncertainty.

After the acquisition and enrichment with meta data, one goal of virtual heritage is *virtual reconstruction*, where single fragments are assembled. Here, research focuses on different degrees of computer assistance, from fully automatic solutions to interactive puzzles. While fully automatic solutions appear promising, they are often difficult to apply in practice. Reasons for that can be the large amount of fragments with arbitrary shape, missing pieces and abraded shapes [11]. This can result in time-consuming manual post-processing or in tailoring different algorithms to special types of artifacts. As examples for the automatic approach, Derech et al. assemble frescos, i.e. 2.5D puzzles with color information [11] and Huang et al. [21], who combine mesh processing methods, registration and pairwise matching of fragments. The problem of automatic assembly can be simplified with the aid of similar completed reconstructions. Gunz et al. [18] achieve this by using a library of complete skulls. Vote et al. [51] also present archaeological analysis tools combined with visualization techniques.

We decided for an interactive solution instead. Here, related works are systems that support solving a puzzle of 3D surfaces for e.g. anatomy education [36, 40, 43, 45], engineering [22] and product design applications [50]. Jurda et al. presented a VR system for the digital restoration of human skeletal remains [9, 23]. Three sets of fragmented skulls were assembled by 20 participants with a VR prototype and a desktop prototype. They compared the systems regarding time, geometric properties and convenience of use. Their results show that interactive restoration takes approximately *half* of the time as a restoration controlled via a desktop PC. Furthermore, the assembled fragments showed less errors and lower variability with the VR system. In contrast to our work, Jurda et al. restored human skulls where the assembled shape is known to a large extent. Additionally, their most difficult puzzle consists of 17 pieces, only 4.1 % of the amount of our funerary monument.

3 Material

Our case study is a funerary monument that was constructed around 1610 inside the Magdeburg Cathedral. During World War II, it was destroyed on 18th September 1944 and the damaged remains of the main structure are still mounted on the wall (see Figure 2). Beside this funerary monument, another funerary monument from the same sculptor was destroyed as well. Overall, 415 fragments were secured after the war damage. The majority of these pieces belongs to the first monument, however, the exact number is unclear.

3.1 Digitization of Fragments

The digitization of the individual fragments included two steps. First, the remaining funerary monument that was still mounted on the wall was scanned. Second, the individual fragments were digitized.

For the acquisition of the wall-mounted funerary monument, we used the hand-held scanner *Zscanner 800* (3D Systems, U.S.A.) which provides an accuracy of 0.04 mm. For orientation, the scanner needs reference markers that were glued temporarily on the funerary monument. Two overlapping meshes were obtained, registered and reduced to 12 % of their original resolution with the mesh processing software *MeshLab*. The final surface contains 1,063,447 triangles.

The scanning of the individual fragments was performed with the *ATOS Compact Scan 2M* (Carl Zeiss AG, Germany). This structured-light scanner projects stripe patterns onto fragments and derives the surface from it. Each fragment was scanned from multiple angles and converted to a surface with the scanner's software. The 415

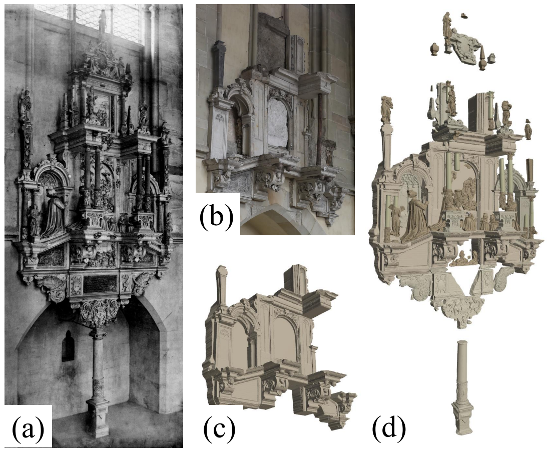


Figure 2: This overview shows the original funerary monument in 1891 (a, image by FLOTWELL) and how it looks today (b) after the damage through World War II. In (c), the digitized version of (b) can be seen, which was the starting point of the assembly. The finalized virtual reconstruction is visualized in (d).

fragments resulted in 8.22 GB of data (smallest fragment 0.9 MB, largest fragment 180 MB, avg. 20 MB per fragment).

Beside the digitization of the fragments, additional meta data was recorded for each piece. This was done by two restorers in 1995 in an inventory recording. This meta information contains a unique identifier, properties such as material, condition and possible connections to other pieces.

3.2 Creating Levels of Detail Automatically

The resulting data sets of the individual fragments and the wall-mounted funerary monument were too large to be used directly in a real-time VR application. A worst-case scenario of displaying all fragments at once results in around 369 million triangles to render. Therefore, we reduced the resolution by using MeshLab's *Quadric Edge Collapse Decimation* algorithm. We approached this in a trial-and-error process. To find a reduction boundary that can be applied to all fragments without risking to loose important details, we investigated characteristic pieces such as a plate of weapons with an inscription (see Figure 3). Changes in the inscription started becoming noticeable after reducing the resolution to approx. 30 %. Reducing all fragments to 30 % results in approx. 111 million triangles, which is still too much for a real-time application.

Initially, we tested texture baking to solve this issue. This, however, is not practical for a large number of fragments. Since not all fragments can be investigated in close-up views at the same time, we created six levels of detail (LODs), showing a low-resolution version for distant fragments and high-resolution models for close fragments (see Figure 3). To create these LODs automatically, we wrote a Python script that executes MeshLab with the reduction algorithm and saves the mesh in its reduced form. The resulting six models were combined into one *fbx*-file automatically with another Python script that uses the Python API of Blender (Blender Foundation).

4 VR System for Restoration

In this section, we first describe the requirements for the restoration. Based on this, the assembly task was divided into three consecutive steps: (1) getting an overview of all fragments and explore them, (2) grabbing pieces and aligning them coarsely to test different assembly options, and (3) precisely moving fragments and connect them from smaller sub-puzzles to larger ones. These steps and their realization are explained after the requirements. The interaction techniques are discussed in more detail because they were iterated several times during the development (Section 5).

The application was realized with the game engine Unity v2019.3.11f1 (Unity Technologies, U.S.A.). As a basis for the VR development, the SteamVR plugin 1.2.3 was used as an interface between the HTC Vive headset and Unity. The interaction was built on top of the Virtual Reality Toolkit (VRTK).

4.1 Requirements

The following requirements were derived after analyzing the process of traditional restoration, interviewing the restorer and collecting requirements for the VR application as well as technical boundaries reasoned by the amount of fragments.

R1 – All fragments need to be represented simultaneously. Ideally, the restorer can see all fragments at once because there are similar pieces that need to be compared to each other. The restorer needs to be supported to either look for a specific fragment or a general property, such as height, material or type.

R2 – Scaling should be provided and applied globally. Due to the varying size of individual pieces (under 10 cm to over 2 m), it is necessary to scale them to make them easy to handle. If it would be possible to scale pieces individually, their relative size would be incorrect. This would complicate finding fitting pieces. Therefore, a change in scale should be applied to all fragments simultaneously.

R3 – Fragments should be positioned quickly and precisely. To test several assembly possibilities, the restorer should be able to align pieces quickly for a plausibility check. If a fitting configuration is found, fine adjustments should be possible to align pieces precisely and connect them to sub-puzzles. These sub-puzzles should allow the same interaction to create larger parts gradually.

R4 – Interaction should be natural and easy to understand. Restorers are mainly doing practical work and usually have limited experience with 3D user interfaces. The VR interactions and representation of fragments should therefore favor natural manipulation techniques and visualizations that are similar to the practical work instead of more powerful but complicated ones. The interaction hand should not influence the functionality, i.e. both hands should have mirrored interaction possibilities.

R5 – The VR environment should motivate and engage the user. The assembly task should be embedded into an environment that is either similar to the typical work environment of the restorer or be equal to the environment in which the physical reconstruction should be build. This may motivate the user, increases the feeling of presence and allows for an improved imagination of the end result.

4.2 Getting an overview: Configurable Self-arranging Fragment Wall

According to R1 and R4, all fragments need to be represented simultaneously and be searchable in a natural and easy way. This allows the restorer to get an overview of all fragments, identify suitable pieces, and look for specific ones.

Making all fragments accessible. Our first idea was a search user interface (SUI) that is presented on one VR controller and is connected to the database of fragments. The restorer defines properties and refines them until one or a group of matching fragments is found. These fragments could then be taken out of the database and be summoned to the virtual environment. This idea, however, has shortcomings regarding the requirement R1 and R4. First, it is difficult to get an overview of all pieces. Second, if the user has a specific fragment in mind but is not able to formulate a search query, it is challenging to find it (similar to the paradox in information retrieval with "the need to describe that which you do not know in order to find it" [20]). Third, hiding all fragments behind a search interface limits the ability to explore all fragments at once.

Instead, we decided to have a permanent physical representation of the fragment database. By showing all pieces simultaneously,

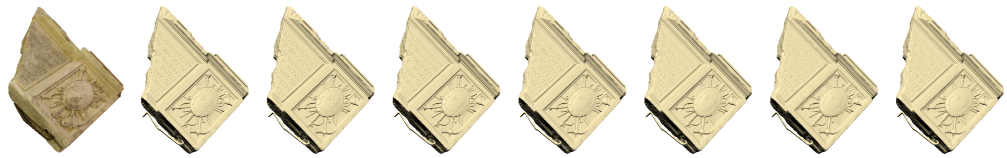


	Photo	Original Scan	LOD 0	LOD 1	LOD 2	LOD 3	LOD 4	LOD 5
Percentage		100%	30%	20%	10%	5%	3%	2%
Triangles		3,048,128	914,424	609,611	304,801	152,404	91,439	60,961

Figure 3: Scanning the *plate of weapons* resulted in a high-resolution mesh that was not usable in the real-time application. Reducing its resolution by 30% (LOD 0) is possible without noticeable differences in the inscription. For each fragment, we create six levels of detail.

the restorer always has an overview and is able to explore them but can still inspect individual fragments closely. This overview, however, needs physical space. Furthermore, the fragments have to be presented in a way that allows the user to recognize them easily. Therefore, we organize the fragments in a 2D grid, forming a wall in front of the user. This wall first expands horizontally until the available space (or a defined maximum threshold) is reached. If there is no space left, it expands vertically into the sky.

The orientation of individual fragments plays a key role in how organized the wall looks. Also, the recognizeability of single pieces is strongly affected by their orientation (see Figure 4). Therefore, similar pieces should be oriented similarly and each fragment should be displayed such that a large amount of its surface is visible. Finding this orientation manually would be too cumbersome. Therefore, we performed a principal component analysis (PCA) on all vertices on a fragment. The PCA creates a local coordinate system and calculates the direction of the largest diameter. This was realized with the machine learning framework *Accord.NET*. The *first* obtained principle component is aligned with the up-direction, which results in fragments standing upright. The *second* principle component is used to align a fragment along the wall, resulting in a large proportion of a fragment being orientated *perpendicular* to the wall. This allows the user to see a large part of each fragment (see Figure 4). A limitation of this approach is observable for fragments such as plates. Here, the side with a motive and the fractured backside are ambiguous, which may lead to showing the wrong side (see Figure 4). Furthermore, this approach can lead to statues standing upside down.

Rearrange the Wall with Grouping and Sorting. The fragments inside the wall can be rearranged via grouping and sorting. Here, the granularity to define properties is a trade-off between flexibility and restriction. We decided for a restrictive approach in favor of ease of use (R4) by offering pre-defined grouping and sorting options with a menu (see Figure 5). However, the implemented approach is easily extendable to an interface with more control.

The general idea is to define *grouping properties* (nominal or ordinal) first and a *sorting property* secondly (ordinal or numerical). After selecting a grouping property (type, location, material, cluster), the available horizontal space is divided into the amount of possible groups (sandstone, alabaster, etc.). Within each group, the fragments are sorted according to their sorting property (id, volume, height). Now, the fragments are positioned in a row from left to right in ascending or descending order (e.g. from low to high volume). If there is not enough available space for the next fragment, it starts in a new row that is moved upwards by the amount of the fragment with the tallest height. Again, the following fragments are positioned in a row from left to right until all pieces of the group are positioned.

The grouping property *type* was derived from the textual descriptions of individual fragments. These texts were analyzed for keywords such as “statues”, “relief” or “column”, which served as categories for this group. Another particularity is the possibility to set *clustering* as a group property and specify the number of clusters. If this is set, the chosen sorting property is used for a k-means clustering. This allows the restorer to divide all fragments regarding their, e.g. volume into a desired number of groups.

After changing a property, the fragment wall has to be rearranged. For this, three animation transitions were investigated:

1. Instant reposition – very fast, but does not allow to follow fragments and breaks the immersion of a large physical wall.
2. Fading out, reposition and fading in – we tested this with alpha blending and scaling. Although the impression of persistent fragments is improved, the fragments appear very light-weight. Furthermore, it is not possible to follow a fragment.
3. Animated movement – this leads to visual clutter and is cognitively demanding, but allows the user to follow a piece visually.

We choose the third option because it is able to communicate more about the relation of fragments, e.g. how many *statues* (old grouping property) are located in the *sandstone* group (new grouping property). To support the user in following fragments, we followed the animation principles stated by Heer and Robertson [19] and implemented *staging* and *staggering*. Staging means to not move all fragments at the same time, but instead moving them in semantic groups. In our case, these semantic groups are defined by new group property. Staggering means to add a little time offset between the movement of fragments within a group.

4.3 Test Assembly Possibilities Quickly with Direct Interaction

Before trying to assemble pieces, they have to be selected and grabbed from the fragment wall. For selection, we implemented raycasting, i.e. shooting a ray from the VR controller. If this ray hits a fragment and a button is pressed, the fragment is grabbed. Due to the large fragment wall and its spacing between fragments, this simple selection technique was sufficient for the reconstruction process. If fragments were too small to select them, the possibility to scale them up (R2) can support the user.

After selection, an appropriate manipulation technique is necessary. With over 400 fragments, the restorer needs to be able to quickly grab, position and rotate pieces (R3). In our fragment data base exist 19 different column shafts that need to be tested against several pedestals, volutes and bases. Thus, frequent grabbing, positioning and rotating of several fragments is necessary. We discuss our chosen manipulation technique based on:

1. the requirement analysis,
2. guidelines presented by Mendes et al. [30] regarding direct and indirect spatial manipulation approaches in immersive VR environments, and
3. the survey from Mendes et al. [28] that gives an overview of manipulation techniques for desktop, semi-immersive and immersive interaction. We focus on the latter that can be used with handheld devices such as VR controllers.

Figure 4: The fragment wall can be rearranged with different grouping and sorting properties. (a) shows a section of the wall without sorting. In (b), the fragments are sorted regarding their height. This is improved in (c). The results of a principal component analysis are used to orient all fragments upright. However, this can result in flipped pieces. The red border shows a fragment were the fractured backside is shown instead of the front. (d) shows all fragments grouped regarding their material and sorted descending regarding their height.

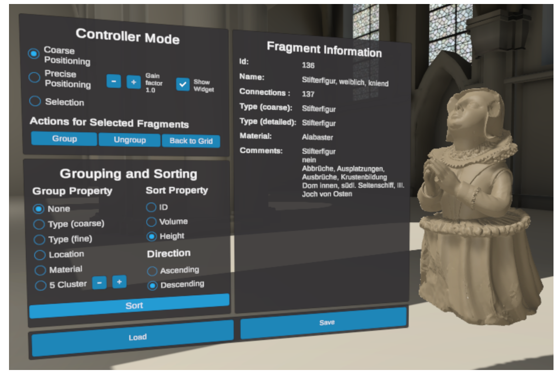


Figure 5: The menu is divided into three areas: the *Controller Mode* allows the restorer to choose between different manipulation and interaction techniques, the *Grouping and Sorting* area allows to define properties to rearrange the fragment wall and the *Fragment Information* panel summarizes information about the lastly selected fragment.

Direct manipulation, where the user's hand movements are mapped to an object directly, is well suited for coarse transformations [30].

Virtual Hand and Raycasting. Although the *Virtual Hand* manipulation [5, 41], where the controller grabs and manipulates objects directly, is the most natural and easy to understand (R4), it is limited by the user's arm length [7]. This disqualifies this technique, since the large number of fragments can be scattered over the virtual space and is out of reach most of the time.

To reach fragments far away, *Raycasting* can be used. After an object is grabbed, the center of rotation is still the controller's position, which could lead to large rotational changes if the object is far away due to the lever-arm effect, which is not desirable. Also, objects far away can only be brought closer in small steps, which leads to clutching [8], i.e. makes frequent grabbing and pulling necessary. This was the first interaction technique we used in our system; but it was abandoned because of these problems.

Go-Go, HOMER and PRISM. The imprecision of *Raycasting* can be solved with the *Go-Go* technique [37], where the user's arm length *grows* non-linearly if the user reaches out for distant objects. After an object is grabbed, it is manipulated with the *Virtual Hand* technique, which lacks precision [6]. Therefore, the *HOMER* technique was introduced (hand-centered object manipulation extending ray-casting), which is a combination of *Raycasting* for selection and scaled *Virtual Hand* for manipulation [6]. An extension of this is used in our system. The calculation of the orientation of the grabbed object is the same as with the *Virtual Hand* technique. The translation, however, is scaled by a factor that is defined by the distance from the user's hand to their torso. This makes it easy to get objects close to the user quickly and still have control over rotations. However, it is difficult to move objects far away from the user. Again, these techniques support grabbing objects that are out of reach and positioning them roughly and quickly (R1). However, the precision can be further improved by extending these techniques. We want to allow an initial aligning of pieces that is as accurate as possible, since this serves as a starting point for the following fine-grained interaction technique.

The basis for the *PRISM* technique [13, 14] is the *Virtual Hand* technique. Fundamentally, the technique analyzes the hand movement speed to assume the user's intent. Fast movements indicate that users do not want to be precise and slow movements indicate precise interaction (i.e. the control/display ratio is increased).

Voodoo Doll and World in Miniature. Another category of techniques does not manipulate the objects directly, but instead copies of them. Focusing especially on the problem of objects with different sizes, the *Voodoo Doll* technique was proposed by Pierce et al. [35]. This technique creates copies of the selected objects (dolls) inside the user's hand. The relative position of one doll in each hand is transferred to their original objects. This technique would be suitable for our application to position two fragments in relation to each other coarsely. However, a problem would arise for the funerary monument in an advanced puzzle state. Here, sub-puzzles with varying size need to be connected, which could not be handled bi-manually practically. A different solution for the out-of-reach problem is the *World in Miniature* [46]. Since there are over 400 fragments with strongly varying sizes, this would not be suitable for our application.

Hybrid Techniques were suggested, e.g. *Scaled HOMER* [53] (*HOMER* combined with *PRISM*) and an approach by Auteri et al. [2] (*Go-Go* combined with *PRISM*). Both techniques are improved by applying a gain to the translation of the object depending on the speed of the hand movement. This results in a higher precision on slower hand movements. There is no study that directly compares these two techniques. Since *HOMER* already performed well and the extension to *Scaled HOMER* improved it especially for distant objects, we used this for coarse 3D manipulation,

4.4 Precise Assembly of Pieces with Individual DOF Manipulation

After identifying fragments that probably match, the restorer needs fine control over translation and rotation to adjust the coarse position (R3). Mendes et al. [30] suggest indirect interaction that separates each DOF individually. This separation is considered as a form of placement and rotation constraint. Another type of constraint is snapping [25], which could not be used in our scenario, since our fragments do not perfectly fit together.

Mendes et al. [30] compared *Virtual Hand* [5], *PRISM* [14] and a widget-based approach [10] that only allows to manipulate one DOF. The widget performed best in almost all docking tasks regarding accuracy. However, it took more time in complex tasks compared to, e.g. the *Virtual Hand*. This would be acceptable in our application, since the user is already supported with a dedicated manipulation technique for fast transformations (*Scaled HOMER*).

The beneficial properties of DOF separation widgets led to the development of new widgets that make the separate DOFs more accessible, combine DOFs or derive the chosen DOF based on the user's hand movement. Nguyen et al. tried to offer all manipulations with a single widget. However, their triangle-based widget with three handles [48] and the extension with seven handles [33] did not perform well due to its complexity. Mendes et al. [31] also tried to improve 3D manipulation and presented *MAiOR*, which combines the achieved benefits by DOF separation and naturalness of 6DOF. Their study could not show advantages of their technique.

MyoungGon and JungHyun [24] compared separated, unseparated, and switching between one, two, and three DOFs. Switching performed better regarding time, but similar regarding precision. The switching between DOFs is triggered by a complex widget and a combination of one-handed and bi-manual interaction. Additionally, their study was performed exclusively with computer science students. Although this approach could result in a better performance regarding time, we assume that the interaction for switching is too complicated to be used in our scenario (R4).

Therefore, we implemented a widget with an exclusive handle for each DOF (see Figure 6). If this does not offer enough precision for the restorer, it is possible to adjust a gain factor that scales the translation and rotation of each manipulated DOF.

4.5 Menu

The restorer can summon and hide a menu that is part of the virtual environment by pressing a dedicated button on the VR controller (see Figure 5). All actions and settings can be executed via ray-based interaction. This menu can be moved around with a restricted Scaled HOMER. Its position can be changed within limits so that it cannot be positioned too far away and it is always facing the user.

The menu is divided into three areas: controller mode, grouping and sorting, and fragment information. The *controller mode* options

Figure 6: For precise interaction a 6DOF widget can be used that allows interaction with a single DOF depending on the grabbed handle. The precision can be increased by adjusting a gain factor that is multiplied with the movement and rotational delta.

allow the user to change the manipulation mode from coarse positioning (Scaled HOMER), over precise positioning (Virtual Hand & widget for individual DOF manipulation) to selection. The gain factor of the precise positioning mode can be adjusted with buttons and influences the Virtual Hand movement as well as the individual DOF manipulation. Furthermore, selected pieces can be grouped, ungrouped or moved back into the fragment wall by pressing buttons on the menu. The second area allows the restorer to choose *grouping* and *sorting* properties and eventually execute the rearranging action of the fragment wall. The third area displays information of the selected fragment, e.g., id, material and type of comments.

4.6 Assembly, Scaling and Teleportation

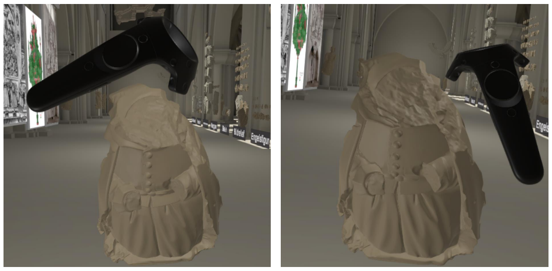
After the restorer has aligned fragments, they can be fixated relative to each other. For that, the selection mode has to be activated. This allows to highlight individual pieces via ray-based interaction. After pressing the *group* button in the menu, all highlighted fragments are *glued* together. This new group is now handled like a single fragment. This allows the restorer to reconstruct the funerary monument by first assembling sub-puzzles. These sub-puzzles can then be connected to other sub-puzzles, forming larger parts of the final reconstruction. Disassembly is implemented similarly. The user first selects a sub-puzzle and then presses the *ungroup* button.

To scale all fragments globally (R2), the grip buttons of both VR controllers have to be pressed at the same time. Moving the hands apart after that increases the size of all fragments and moving them closer together decreases their size. Since the fragments can be scaled as large as the restorer needs them to be, especially the fragment wall can take a large amount of virtual space. Room-scale VR is not enough to navigate to all fragments. Therefore, teleportation is implemented, which can be executed by pointing the ray at the bottom and pressing a button on the controller.

4.7 Environment

The virtual environment should be created in a way that motivates and engages the user (R5). Furthermore, using an environment similar to the place where the final real reconstruction should be restored is ideal, as it allows the restorer to imagine its final impact and size more realistically. We followed this idea and used a 3D model of the Magdeburg Cathedral (see Figure 1).

Lighting. For the general lighting of the virtual environment, two approaches were considered. The first one being more synthetic, but informative. Here, the main light source is a directional head light. This allows sufficient illumination of each investigated fragment. Shadows were disabled to prevent occlusion of parts by other fragments. Although this approach may improve the perception of fragments, it contradicts R5, as the environment would not be natural. Instead, a realistic approach is followed. First, a directional light is oriented in way that it reproduces the sun position of an early morning and illuminates the interior of the Magdeburg Cathedral



(a) (b)

Figure 7: Point lights are attached to the controller and allow the inspection of abraded surfaces. In (a), the elevations of the surface can hardly be seen, which is improved in (b).

brightly through the windows. Unity's global illumination feature was used to create an equal illumination and soften the shadows. Real-time shadows were allowed to make the environment more realistic. However, this could result in fragments throwing shadows on objects behind them. To compensate for this and in cases were the orientation of the main light is unfavorable, point lights were positioned on each controller, giving the user a flashlight in each hand. This allows to light fragments from different angles which helps to investigate fractured borders and the surface (see Figure 7).

Embedding Photographs. A positive aspect of several historic artifacts that were destroyed during the 20th century is that there exists a variety of photographs of the original undamaged condition. Similar to 2D puzzles, these templates are helpful to assemble the puzzle. Therefore, we collected images from archives and embedded them into the virtual environment (see Figure 1, right). They display the undamaged funerary monument from different angles as well as detailed regions of reliefs, plates and statues. The photographs are working like other interactive objects, i.e. the user is able to grab them and compare them with the 3D restoration.

5 Evaluation

The application was developed in an iterative process with a qualitative evaluation. The whole process of obtaining requirements over implementing first prototypes to a final application that allows the virtual restoration was accompanied by a restorer with 17 years of professional experience. Over a course of 14 assembly sessions that took around 1.5 hours each, the restorer and a computer scientist used the application alternatingly to improve it and assemble the puzzle at the same time. Both were in the same room. The roles slightly differed depending on who was using the application. If the restorer used it, the computer scientist analyzed interactions, took notes, and encouraged the restorer to think aloud.

If the computer scientist used the application, the restorer led the assembly by stating goals (e.g., "today we assemble all fragments that belong to columns"). Simultaneously, she took further material (photos and notes) to support assembly decisions. This approach of alternating users was beneficial as it allowed to perform studies of 1.5 hours without inducing cybersickness or fatigue.

Figure 8 shows a summary of the assembly progress. Overall, $\bar{x} = 13$ ($\sigma = 13.6$) fragments were assembled per session. In average, $\bar{x} = 11.4$ ($\sigma = 23.7$) were categorized as *unsure*, indicating that these fragments are either part of the other funerary monument or their location cannot be determined. Finally, $\bar{x} = 5.3$ ($\sigma = 10$) were excluded per session, indicating that these belong to the other funerary monument. The amount of variance differs strongly for these groups. While the progress of assembled pieces is steady over all sessions, most fragments were categorized *unsure* or *excluded* during the last session, resulting in a high variance. The reason for that is that the most distinctive fragments were assembled at the beginning. The remaining fragments were mostly too small (3 – 8 cm) to make a definitive decision about their position. For example, several *coats of arms* could not be assembled, since there was no photograph that supported an assignment.

In the following, selected sessions are discussed as they represent the iterative development and improvement of the application. After that, observations during the assembly sessions are described followed by a collection of remarks from the restorer.

5.1 Technical Advancements over Assembly Sessions

Over the first five sessions, the application was improved. After that, no further functionality changes were necessary. All interaction techniques were used within the evaluation.

Session 1 & 2. In these sessions, an early prototype was discussed with the restorer. She stated that the resolution of individual pieces was not high enough to see fine details. This led to the implementation of the LODs (see Section 3.2) to allow the inspection of high-resolution meshes if they are close to the user.

Furthermore, it was stated that photographs inside the virtual environment would be useful (see Section 4.7). Over the next sessions, we added more photographs as we got access to them.

Although an initial version of grouping and sorting already existed, a possibility to group elements according to their type was requested, which was implemented afterwards (see Section 4.2).

The initial ray-casting interaction for object manipulation was abandoned due to the unwanted large rotational changes for distant fragments and the necessary clutching. This interaction was not only cumbersome, but made it impossible to precisely align two fragments to each other. Instead, a track beam was implemented that attracts fragments close to the user after selection. After that, the Virtual Hand method was used for precise interaction.

Session 3. This session was the first one with achieved progress (see Figure 8), as the track beam and Virtual Hand allowed precise alignment and assembly of several pieces. The track beam attracted a selected fragment until it was reachable by the user. While this was useful for small fragments, large pieces came too close for easy interaction. As a solution, we implemented the track beam to change the distance in relation to the occupied field of view. However, large fragments were positioned too far away after that. Thus, the track beam was abandoned in favor of Scaled HOMER. For precise manipulation, the 6DOF widget with DOF separation was added.

Until now, printouts and notes of the meta data for each fragment were used. Switching between VR and printout was not practical, which led to the integration of the fragment database into the application (see Section 3.1) and its visualization in an info panel (see Section 4.5). The integrated meta data allowed to visualize the fragment differently depending on their material property. Additionally, for some fragments, potential connections to other pieces were noted in the database, which supported the assembly process.

The restorer noticed that the ability to see fine cracks, gaps and surface texture depends on the orientation of the fragment to the directional light. To enable a flexible and natural adjustment of the lighting conditions, point lights were attached to each controller.

Session 4 & 5. During several occasions, the restorer wanted to manipulate the fragments directly with the Virtual Hand mode, but that was not possible since the 6DOF widget occluded parts of it. Therefore, we implemented an option to disable it temporally. The 6DOF widget was not used anymore for the remaining sessions. Instead, the Virtual Hand method in combination with the gain factor was used exclusively to assemble the remaining fragments. Discussions with the restorer revealed two reasons for that: (1) there is no universal solution for the correct axis orientation of the 6DOF widget. We experimented with aligning them locally to the result of the PCA (see Section 4.2). While this was ideal for fragments such as columns, it was not helpful for pieces were the main components of PCA did not align with the general piece orientation. Therefore,

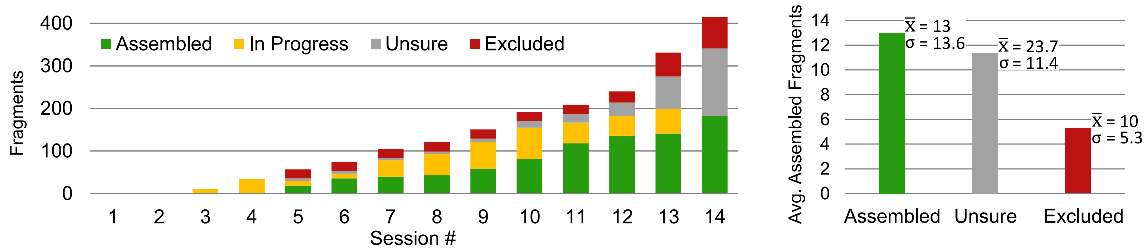


Figure 8: The progress over all 14 assembly sessions of the restorer and computer scientist is depicted (left). The average progress (right) shows a strong variance between the sessions.

we tested to align the widget axis to the world axis. This, however, was more laborious compared to only using the Virtual Hand in combination with the gain factor.

5.2 Observations in Assembly Sessions

Session 4 & 5. During sessions four and five, two reliefs were assembled showing the *Raising of Lazarus* and the *crucifixion*. From both scenes, close-up photographs existed in the virtual image gallery (see Section 4.7). Although initially not planned that way, these images were used as a direct template to support the assembly. First, the global scale was aligned so that the funerary monument and image size match. Then, the image was moved to the position were the associated fragments should be placed in the final assembly. This allowed the correct positioning of fragments in mid-air, even without a direct connection to another fragment (see Figure 9).

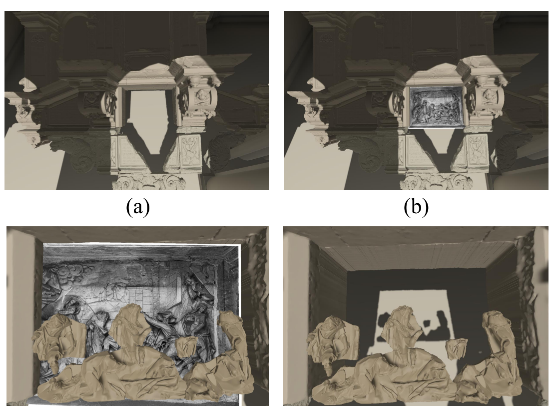


Figure 9: In (a), the empty space of the *Raising of Lazarus* relief can be seen. By scaling the funeral monument to the same size as the image of this relief, the restorer can position the image in the empty space (b) and use it as a template to position fragments correctly (c), even no direct connections to the outer fragments exist (d).

Session 7, 8, & 11. Within these sessions, statues and columns were assembled. Both have in common that individual components form the whole structure. The statues consist of bodies, heads, garments and arms. Columns consist of a column shaft, pedestals and a capital. However, each type exists in similar variants. This leads to a large number of assembly possibilities. The coarse interaction allowed to position, e.g., all bodies in a row and quickly test one head against all of them within minutes. Doing this in reality would take hours.

Session 8 & 14. In these sessions, the columns were built and assembled. To differentiate the column shafts, the restorer tried to compare their relative size. Positioning them side by side was not sufficient to find the larger one. Instead, this was done by penetrating one shaft directly into another shaft and see which one protrudes.

5.3 Additional Remarks from the Restorer

The restorer suggested further improvements. Although the realistic environment was engaging, it could also be distracting. In an early stage of the assembly, an alternative simplistic environment should be offered. Furthermore, a possibility to take distance measurements would be helpful to, e.g. distinguish columns, as two groups with a different diameter existed. Finally, a bubble level tool that supports aligning fragments vertically or horizontally would be helpful.

6 Conclusion

We presented a VR system for the digital restoration of a funerary monument. A configurable self-arranging fragment wall to organize all 415 fragments was presented that groups or clusters fragments according to user-defined properties. Additionally, coarse manipulation was supported with a Scaled HOMER approach and precise manipulation with a combination of the Virtual Hand method and a widget that allows the manipulation of 6DOFs individually. Together with a restorer, the system was improved iteratively and the monument was assembled virtually which is the basis for a following real restoration. Fundamentally, the application can be reused for other broken artifacts by providing 3D surface meshes of individual pieces. However, to fully make use of the grouping and sorting functionality, meta information on each 3D mesh is necessary.

The iterative evaluation improved the application to a level where the virtual restoration is possible. Still, it needs to be tested if similar results can be achieved by other users. Performing a quantitative study could be another next step. Although previous studies could show that VR systems offer quicker and less erroneous restorations compared to 3D modeling software [9, 23], a comparison of aspects such as fatigue would be interesting. Additionally, a usability study, even with non-expert users, could reveal usability issues that were not discovered so far.

During the last puzzle session, 84 pieces were excluded or put into the *unsure* category. Here, fragments had to be selected one-by-one which was cumbersome. A possibility for selecting a group of objects would be useful [1]. Selecting small distant fragments was only possible by scaling them up first. This could be improved by using selection techniques for high-density grid environments [26], velocity-based methods [16] or iterative techniques [29]. A possibility to improve the precise interaction is to realize a physics inspired collision detection between pieces.

An interesting next step of the physical reconstruction relates to 3D printing. Areas of missing fragments can be exactly traced by following the border of surrounding fragments. This area can be converted to a surface, which represents the missing space. A 3D print of this would then perfectly fit into the blank space.

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