Colonia 3D
Communication of Virtual 3D Reconstructions in Public Spaces

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Abstract

The communication of cultural heritage in public spaces such as museums or exhibitions, gain more and more importance during the last years. The possibilities of interactive 3D applications open a new degree of freedom beyond the mere presentation of static visualizations, such as pre-produced video or image data. A user is now able to directly interact with 3D virtual environments that enable the depiction and exploration of digital cultural heritage artifacts in real-time. However, such technology requires concepts and strategies for guiding a user throughout these scenarios, since varying levels of experiences within interactive media can be assumed. This paper presents a concept as well as implementation for communication of digital cultural heritage in public spaces, by example of the project Roman Cologne. It describes the results achieved by an interdisciplinary team of archaeologists, designers, and computer graphics engineers with the aim to virtually reconstruct an interactive high-detail 3D city model of Roman Cologne.

KEY WORDS: High-detail 3D Models, Virtual Reality, Real-Time 3D Visualization, Museum, Roman Cologne

1. Introduction

1.1 Motivation

Virtual 3D reconstructions of archaeological excavation sites, artifacts, and architecture play an important role preserving our cultural heritage for future generations. Used in combination with interactive visualization technology, they become a powerful tool to support scientific discussions among experts and to present important archaeological facts to broad audiences using museum and edutainment applications. However, the creation and interactive exploration of high-detailed 3D reconstructions is still a challenge for the community (Santos et al. 2006; Kuchar et al. 2007) and most projects finally result in still images, pre-rendered animation videos, or QuickTime(r) panoramas as a compromise between visual quality and interactivity (e.g., Debevec, 2005; Almagro et al. 2006).

As an interdisciplinary team, consisting of archaeologists, designers, and computer graphic engineers, the project "Visualization of Roman Cologne" started, with the vision to overcome these limitations. Our aim was to construct high-detail virtual 3D models and a visualization framework that enables their interactive exploration and presentation (Fig. 1).

This paper presents the results of the combined expertise of all teams. It can be read as a guideline for similar future projects, e.g., to setup a collaborative content creation process, select appropriate data exchange formats, or to apply the presented visualization and optimization techniques to other domains of virtual archaeology.

1.2 Challenges

With the beginning of the digital revolution in the second half of the 20th century, a new era heralded for all information-related activities, redefining how information is retrieved in economic, social and technological systems today. The communication of cultural heritage is one of these areas that experienced a continuous growth during this time, where it leveraged from the digitalization for a long-ranging preservation and efficient communication of context-sensitive information.

With major interest, the reconstruction of archaeological excavation sites emerged as a powerful tool to communicate archaeological features and cultural knowledge, not only to experts, but also to broad audiences of exhibitions or museums. A continuation of this trend for these public spaces involves digitized cultural heritage, in order to enable people an immersive exploration (Heim, 1997) of "collections for inspiration, learning and enjoyment" (Museums Association). With the ongoing advancements on the field of virtual

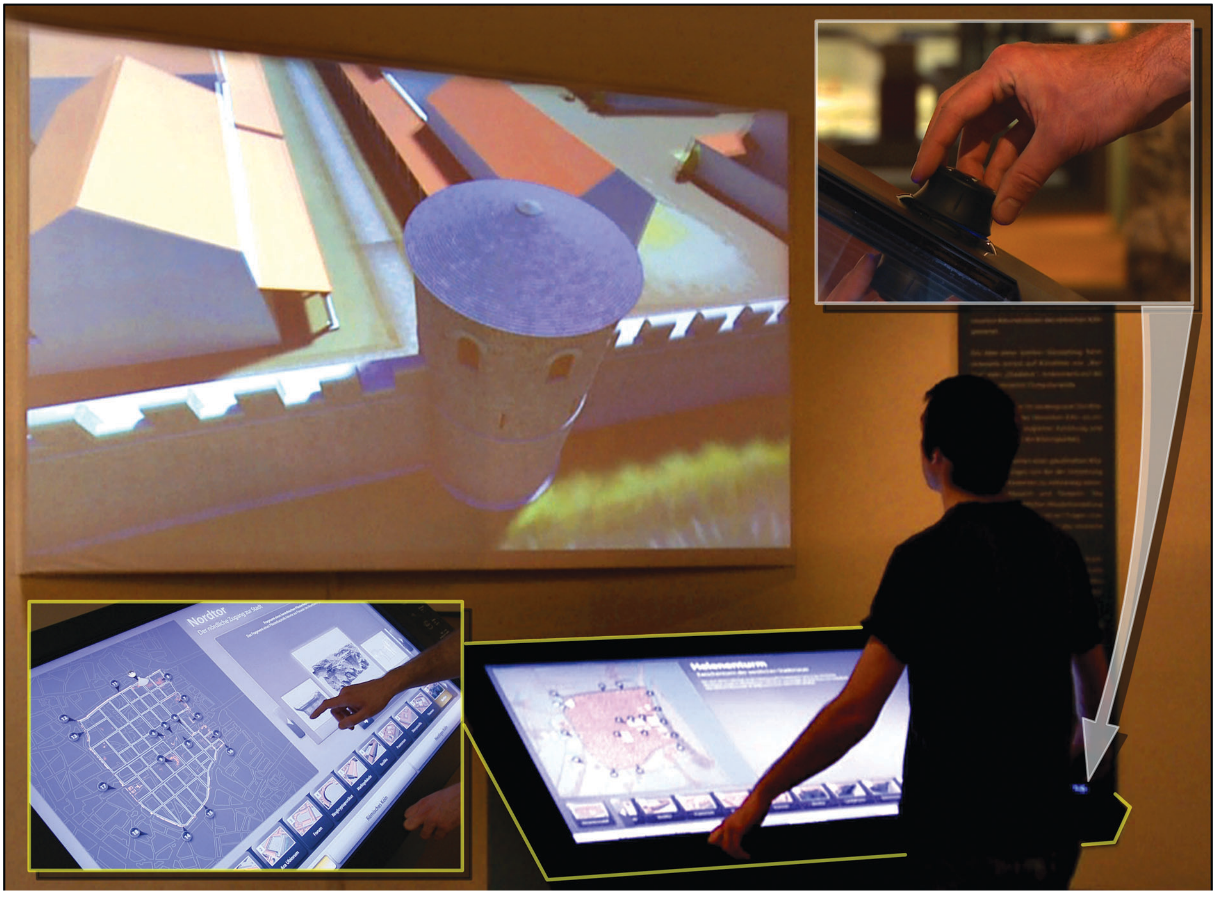


Figure 1: The virtual 3D reconstruction of Roman Cologne and its exhibition setup at the Romano-Germanic Museum in Cologne.

reality over the last decades (Marzuryk & Gervautz, 1996), the coupling with digital cultural heritage has evolved as a promising application for an effective and immersive communication of this context-sensitive information. Here, the visualization with interactive 3D applications opens a new degree of freedom beyond the mere presentation of static visualizations. They allow a user to directly interact with 3D virtual environments and enable the depiction and exploration of digital cultural heritage artifacts in real-time.

However, these scenarios mostly induce highly complex and massive data, as being true to the original is one of the ultimate goals. Consequently, visualization concepts and strategies are required that do not only permit an effective communication of these context-sensitive information, but also guide a user throughout these scenarios, since varying levels of experiences within interactive media can be assumed. Therefore, visualization techniques are required on both, technical level in order to allow a real-time visualization of the reconstructions, and conceptual level for allowing users to interactively explore the environment and perceive this information intuitively.

1.3 Contributions

This paper can be read as a guideline for similar future projects, e.g., to setup a collaborative content creation process, select appropriate data exchange formats, or to apply the presented visualization and optimization techniques to other domains of virtual archaeology (Maass et al., 2008b). To summarize, this paper makes the following contributions to the challenges stated above:

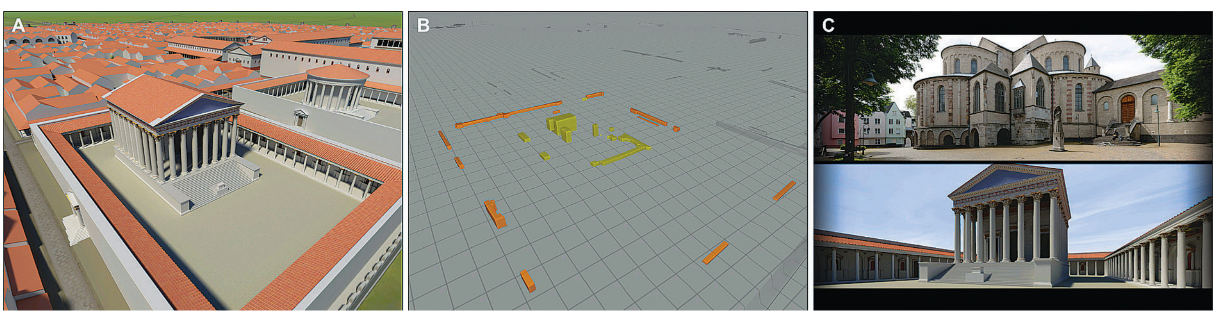
1. We propose a concept for the communication of digital cultural heritage in public spaces, such as museums or exhibitions. This basically comprises the identification and justification of different visual presentation modes (Fig. 2).
2. We further present the research results for a prototypical application and implementation of a client-server model for information communication and human computer interaction in public spaces.
3. We furthermore present the application of these concepts to the project Roman Cologne that is currently and successfully presented as a permanent exhibition in the Romano-Germanic Museum in Cologne.

The remainder of this paper is structured as follows. Section 2 gives an overview to previous and related work. Section 3 presents a brief overview of the different aspects of the project Colonia 3D. Section 4 introduces the presentation concepts used for the exhibition at the Romano-Germanic Museum in Cologne. Section 5 briefly explains implementation aspects and optimization methods applied to the reconstructed 3D models to perform real-time image synthesis. Finally, Section 6 discusses results, concludes this paper, and presents ideas for improvements and further research directions.

2. Previous and Related Work

In this Section, we give an overview of related work that evolved in the areas of virtual reality and the communication of digital cultural

Figure 2: Presentation modes for the communication of digital cultural heritage by the example of Roman Cologne at a single hot spot: (A) reconstruction mode, (B) findings mode, and (C) comparison mode that uses 360° horizontal panoramic views of the ancient and today's Cologne.



heritage. We further outline interaction concepts and installations used in public spaces.

2.1 3D Virtual Environments for Digital Cultural Heritage

Previous projects involve the modelling and rendering of digital cultural heritage in 3D virtual environments. The "3D-Arch" project, e.g., captures exteriors and interiors of castles in northern Italy and models these with different LoDs (level-of-detail) using image-based methods, surveying, laser scanning and floor plans (Remondino et al., 2009). Another example is the 3D reconstruction of ancient fresco paintings for a revival of life in ancient Pompeii, where virtual characters are simulated in real-time using augmented reality (Papagiannakis et al., 2005). Song et al. presented a reconstruction of Peranakans and their culture in the Singapore region using virtual reality (Song et al., 2003). A visualization of four-dimensional data and different time periods is exemplified by the reconstruction of the city of Koblenz (Germany) (Laycock et al., 2008). Here, architectural styles of buildings, building heights and roof styles are altered over time to author a case study for a 4D navigable movie.

To date, only few projects have been presented that enable users a flexible navigation in 3D virtual environments, e.g., an interactive exploration of digital cultural heritage sites in real-time. The Virtual Reality Notre Dame (VRND) project, e.g., builds on a gaming-based 3D engine to facilitate a virtual tour guide with high-resolution imagery at real-time rates (DeLeon & Berry, 2000). Previous work described methodologies how visualization systems can use standard programming languages and APIs (application programming interface) to visualize digital heritage sites in 3D without depending on proprietary commercial 3D game engines, for instance utilizing high-quality illumination techniques such as radiosity-based global illumination (Papagiannakis et al., 2001). Kuchar et al. presented a photorealistic real-time visualization of Friedrichsburg Castle (Germany) (Kuchar et al., 2007). They base on the RadioLab system to perform radiosity lighting with a daylight simulation and a high dynamic range (HDR). Magnenat-Thalmann et al. propose a real-time, 3D virtual simulation of the populated ancient sites of Aspendos and Pompeii, where they facilitate from virtual reality and simulated, dynamic virtual humans for an immersive experience (Magnenat-Thalmann et al., 2006).

Previous work explored rendering techniques that enhance realism and improve the immersion aspect of 3D virtual environments. Besides using regular illumination techniques (Akenine-Möller & Haines, 2002), light scattering can be modelled to include participating media for enhancing the perception of digital heritage sites, which is exemplified by the ancient Egyptian temple of Kalabsha (Gutierrez et al., 2008).

Further, HDR imagery can be used to enhance viewing experiences and to visualize 3D environments with a predictive ancient lighting (Gonçalves et al., 2009). Other work uses crowd simulation to improve realism of virtual environments. For instance, a visualization system can be implemented with a rule-based behaviour to model population within complex 3D environments (Ulicny & Thalmann, 2002).

2.2 Digital Cultural Heritage in Public Spaces

The communication of cultural heritage in public spaces, such as museums or exhibitions, is commonly used for the purpose of study, education and enjoyment. Digital reconstructions of archaeological excavation sites and their interactive visualization emerged as a powerful tool to communicate archaeological features and cultural knowledge to experts and a broad audience. In this domain, virtual reality offers new communication channels, whose use in public spaces statically increased over the past years.

A first application that uses virtual reality for communicating digital heritage is the 3D reconstruction of Dudley Castle (England) that uses a flat screen for presentation (Boland & Johnson, 1996). More sophisticated installations use a CAVE system, where immersion is sustained by projecting visuals on display screens of a cube and where the audience is positioned in the middle (Cruz-Neira et al., 1993). Examples that use a CAVE system are the reconstructions of the Dunhuang caves (Lutz & Weintke, 1999) and an ancient Greek temple in Messene (Christou et al., 2006). A third possibility of virtual reality installations are panoramic screens of cylindrical shape. These are used, e.g., in the Virtual Sculpture Museum of Pietrasanta (Italy), where a panoramic stereo screen of cylindrical shape is used to improve immersion (Carrozzino et al., 2008).

The impact of interactive systems in public spaces using digital artifacts has been demonstrated in previous work. Michael et al. present a comparative study of interactive museums exhibits, where interactive systems have been rated higher over traditional teaching methods in terms of user experience (Michael et al., 2010). Tost and Economou explored the suitability of interactive virtual reality (Pujol Tost & Economou, 2009a). They conclude that virtual reality assists in education purposes, as it allows a “flexible, personalized exploration of a richer quantity of information”. However, virtual reality may lack of immersion and may lower empathic engagement in comparison to an interaction with physical artifacts. Yet virtual reality offers high potential in the reconstruction of no longer existing artifacts. In a second work, Tost and Economou investigate the suitability of immersive virtual reality for education purposes (Pujol Tost & Economou, 2009b). They conclude that the visual, dynamic and interactive character of virtual reality makes it suitable for “spatial phenomena [...], discovery learning and bi-directional communication”.

One of the most challenging issues when communicating digital cultural heritage in public spaces is the installation of interaction facilities that allow an intuitive and consistent navigation, but also allow an exploration of application-specific content. A variety of evaluations of interaction devices for these environments exist, e.g., for common 2D (mouse) and 3D input devices (space mouse) (Petridis et al., 2005; Lepouras et al., 2004). A tactual exploration concept has been presented by the example of the PURE-FORM project, e.g., to enable studies and investigations on digital reconstructions rather than real archaeological finds (Bergamasco et al., 2002). Another work designed a sensor-based installation to reduce the distance between visitors of exhibitions and cultural heritage (Campos et al., 2009). More experimental interaction techniques are explored, amongst others, by Lotte et al., who focus on brain-computer interfaces using imagined movements to perform complex interaction tasks within virtual environments (Lotte et al., 2010).

3. Conceptual Overview

To start the collaborative work, we first setup a content creation pipeline, define the data exchange formats, possible use-cases, and the roles for each team. This process should guarantee that all experts within the teams can operate in their domains without restrictions. Additionally, the pipeline is designed to facilitate three important aspects:

1. Content preservation: The representation and encoding formats of the accumulated primary (3D models) and secondary data (multimedia content) has to ensure its accessibility for future usage.
2. Extensibility: The established pipeline should support the integration of upcoming ideas and new technology in all its stages during the project.
3. Re-usability: The developed framework should be robust, flexible, and easily adaptable to enable its application in other interdisciplinary visualization projects.

3.1 Scientific Reconstruction

To create a complete 3D model representing the ancient town of Cologne, a number of single roman structures and building elements had to be reconstructed first. The reconstruction of these elements, their combination, and arrangement was done by the archaeology

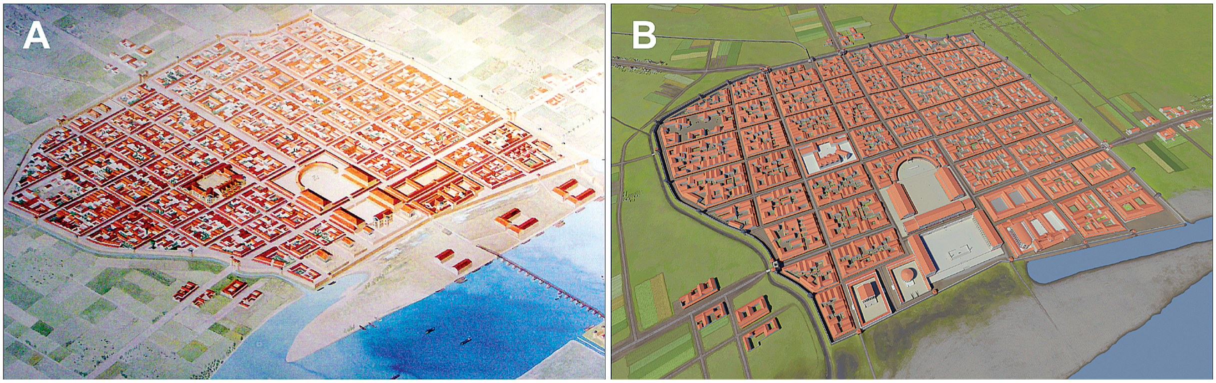
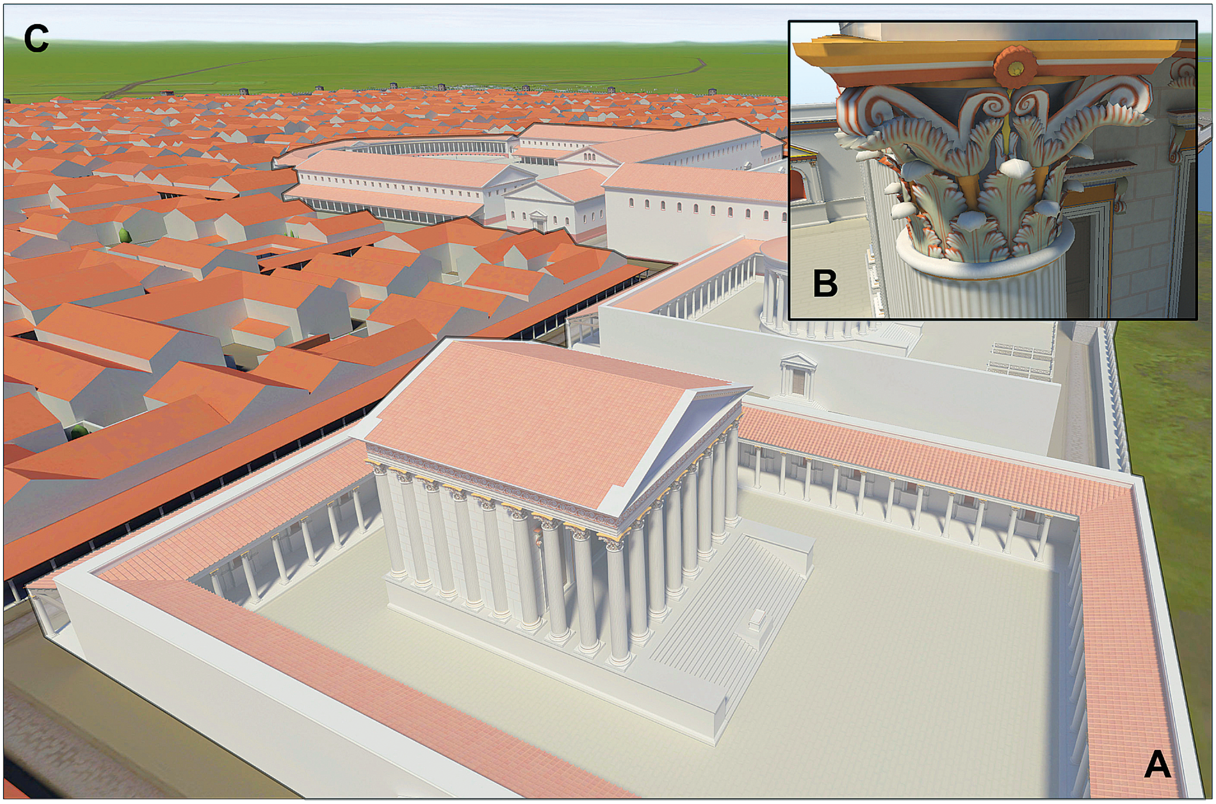


Figure 3: Comparison of an artist drawing and the virtual 3D reconstruction of the ancient Roman Cologne.

Figure 4: Two different levels-of-detail in the virtual 3D reconstruction: (A) detailed buildings of high geometric complexity (B) and low detail structures (C).

experts. For this task, known facts from previous research, results of actual publications (e.g., Irmler, 2004), as well as recent finds of the local department of antiquities of the Romano-Germanic Museum Cologne were considered. Only well-studied buildings, with a scientifically evaluated shape or floor plan, were reconstructed in high detail. Thereby, analogies to reconstructions, done before, were used to derive new reliable 3D models. For all other elements only simple shapes were selected for the reconstructions to communicate the missing evidence (Fig.3 and Fig. 4).



Additionally, a digital terrain model (DTM) (Weibel & Heller, 1991) of the ancient Cologne with building sites and streets was reconstructed to embed the 3D buildings later on. It was derived from a DTM of the present Cologne, whose geo-reference was adapted to the location of finds as well as to known morphological changes in the past. Furthermore, the ancient settlement area was bounded by a plateau and a city wall; structures that can be partially recognized in today's cityscape (Fig. 5).

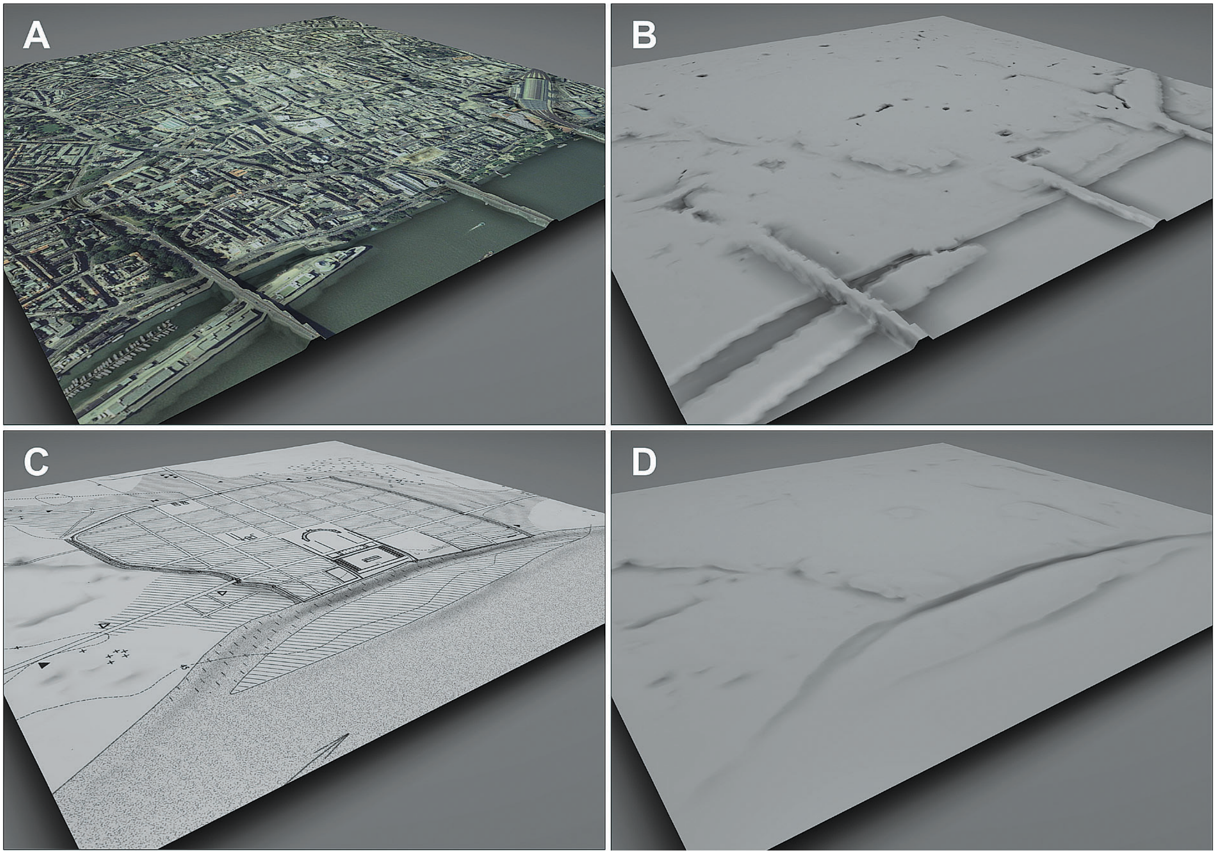


Figure 5: Digital terrain models of today's Cologne (A and B) and the reconstruction (C and D) of the late 1st Century AD.

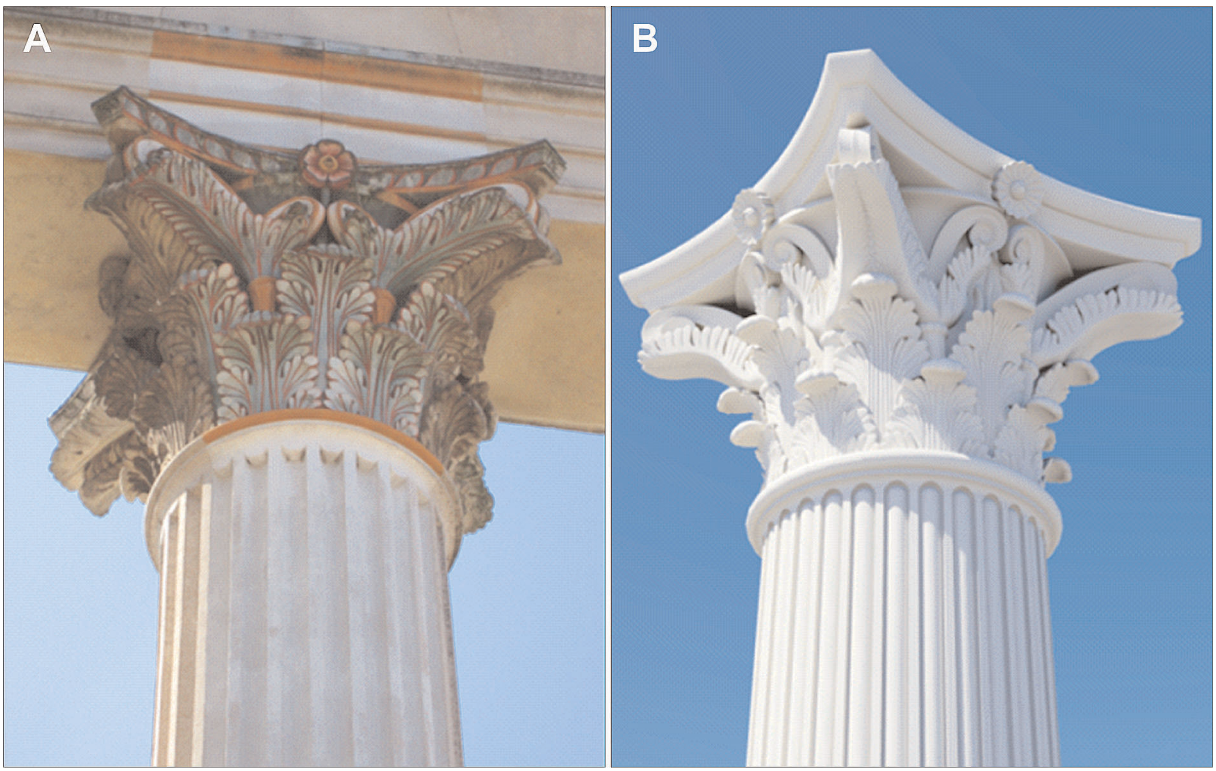
The reconstruction results represent the scientific fundament and are used by the design team to create the virtual 3D models. Therefore, archaeologists deliver all suitable data such as textual descriptions, photographs of artefacts, and highly detailed 2D computer aided design (CAD) drawings (in DWG file format) of building parts and their arrangement to the designers.

3.2 3D Model Creation

Based on this scientific evaluated material, designers create virtual 3D building models for the real-time visualization and Flash(r) content for the presentation of related information. Thereby, one challenge for designers is to balance the classical trade-off between visual quality and suitability for real-time rendering to meet the requirements of the two other groups. On one hand, archaeologists demand for maximum visual quality for every detail. On the other hand, computer graphic engineers rely on low polygonal representations for fast rendering on graphics hardware, to ensure interactivity for the expected number of high-detail building models.

The 2D CAD reconstruction drawings, imported into a 3D modelling tool, serve as blueprints to model single building pieces. Because buildings in Roman architecture can contain a large number of small ornamental elements, which would result in a huge number of polygons within the 3D reconstruction, designers have to work anticipatory. To reduce the geometric complexity, rounded structures, represented by spline curves (Foley et al., 1990) in the CAD drawings, are approximated by polygonal counterparts. Generally, all individual objects are constructed with the least possible amount of polygons while remaining the original shape.

Figure 6: Comparison between a reconstruction of a capital from Xanten at original scale (A) and a virtual 3D reconstruction without textures (B).

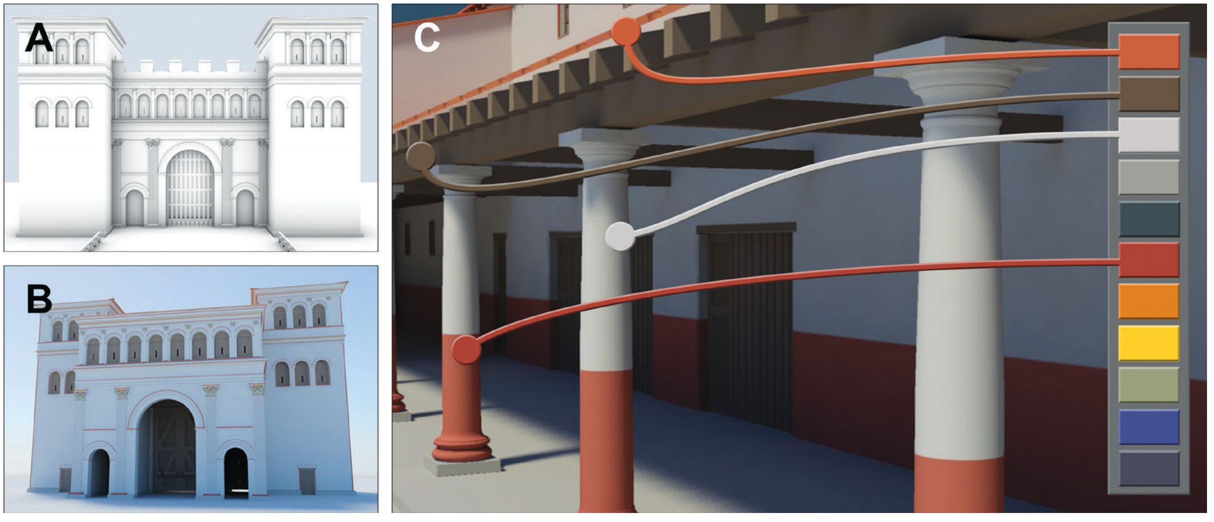


After a library of 3D elements (e.g., capitals, columns, and doors) was created (Fig. 6), these structures are combined to complete buildings and provided with 2D texture-maps representing the respective materials. These material textures are based on colour templates prepared by the archaeologists. Further, static lighting conditions are assumed to enhance the 3D impression of the models and to accelerate rendering. Therefore, the material textures are combined with light maps, which are derived from global illumination simulations. Finally, all building positions are geo-referenced and scaled with respect to the overall 3D scene.

To improve the rendering performance for a scene constructed out of a number of individual 3D models, a further set of optimizations is applied. Because, illumination was pre-computed for static lighting and stored combined with material colours in the surface textures, lighting calculations are turned off during interactive rendering. Appropriate shader programs are used to minimize the processed set of vertex and fragment operations. These programs compute only the model-view and projection transformations for each vertex, and use a single texture look-up to determine the visible colour and intensity for each drawn pixel.

Basically, there are two possibilities for the images synthesis of this visualization mode: photo-realism vs. abstract visualization. For example, in the case of Roman Cologne people often wish to have more realism in texturing and lighting, but archaeologist concerns that this would imply a "finished" reconstruction to the user. We choose an abstract, non-photorealistic, and simple colouring schema to communicate that the visualized reconstruction is only one out of many realities (Fig. 7).

Figure 7: Appearance of the virtual 3D reconstruction: global illumination (A) combined with an abstract colour scheme (B) using a specific colour palette (C).



3.3 Interactive 3D Visualization

Compared to static 2D illustrations, interactive 3D visualizations, presenting the Roman buildings within their context, enable archaeologists to discuss or validate their hypotheses with a direct access to the spatial situation. Thus, it become possible to analyze the arrangement of buildings related to the terrain, their mutual visibility from a pedestrian perspective, or the connectivity regarding to the path network. To support these tasks in virtual archaeology applications, two conditions have to be considered:

1. Scientific users demand for free navigation, allowing them to inspect every detail in the complete 3D scene. They do not accept restrictions to particular areas or viewing angles, such as used for optimizations in 3D computer games.
2. The models delivered to the 3D CG engineers are created with standard DCC tools. Again, compared to specialized level editors or content creation tools, this allows only a limited set of optimizations during the modelling stage.

For these reasons, and because Collada is more a flexible exchange format than an efficient storage or rendering format, the 3D models have to be converted in a pre-processing step into a binary format specific to the renderer. Therefore, we developed a configurable converter tool chain that applies a set of optimizations to each model to prepare it for efficient real-time rendering. To minimize the loading times this converter uses a simple binary format for persistent storage of the optimized 3D model representations. Nevertheless, the Collada representations are not affected and stay preserved as input data for other visualization applications in the future.

Besides model optimization, the second task of the CG team is to develop an application framework for the interactive presentation, analysis, and exploration of the models. To support the need of different end-user groups, this team is responsible for permanent framework extension with enhanced visualization and adaptive navigation techniques.

3.4 Data Management

To exchange 3D models a data format has to be selected that meet the following three criteria:

1. It has to be supported by digital content creation (DCC) tools used by the designers (Cinema4D, 3DSMax).

2. To provide content preservation, the format should be extensible, future proof, and store information lossless.
3. The format should support a minimum set of standard features (e.g., geometric transformations, color and material definitions, geometry instancing, and external references for reusing building elements.

To enable the use of state-of-the-art rendering techniques supported by modern graphics hardware, e.g., multi-texturing or shader programs (Kessenich, 2006), the support of related features by the format is additionally desirable.

We decided on using the Collada exchange format (Arnaud & Barnes 2006; Khronos Group, 2008). It fits all of above requirements, is based on an XML scheme, has an open specification, and is supported by a large number of major 3D hardware and software companies.

Both, the tool chain for model optimization and the visualization application can be completely configured using XML files. This data-driven approach gives the flexibility to easily create and validate new optimization schemes or 3D visualizations scenarios without programming skills.

The XML file for the 3D visualization enables the definition of different visualization scenarios. For each scenario, multiple camera positions and orientations, the 3D models that should be displayed, and a set of navigation constraints can be defined. The camera settings describe predefined views to important elements of the scene. An animated camera movement can be derived by a consecutively interpolation between two camera settings. Navigation constraints help to avoid getting-lost situations. Therefore, a maximum distance to a point in the scene or a minimum height for the observer position, e.g., above the digital terrain, can be specified.

Since we have a separate data basis for 2D content of the client visualization and 3D content of the server, special care is required for the synchronization between these two. For the communication between client and server (Section 4), we use unique global textual identifiers for modes, hot spots, and findings that are mapped by the client and server individually to the respective local content repositories.

In addition to the content creation pipeline described in (Maass et al., 2008b), the geometric representations of the finding meshes are explicitly modelled or triangulated point clouds derived from laser scan data of the original findings. We choose a fixed aspect ratio (16:10) for 2D content creation of the client to minimize sampling artifacts, which would be introduced by rescaling the content otherwise. Both, client

Figure 8: Exemplary images of the reconstruction presentation mode showing different high-detail virtual 3D reconstructions.

and server use a XML data-based file format that allows for easy maintenance and extension. This approach is also suited for a possible data-base binding later on.

The images required for the comparison mode can be obtained by photographs and application screen shoots. In the case of Roman Cologne, we use panoramic images with 360 degrees horizontal field-of-view. After relevant positions are determined within the reconstruction, a photographer acquired real-world images, which are aligned and stitched using Adobe Photoshop(r). Our visualization system can acquire panoramic images using a rendering technique described in (Trapp & Döllner, 2008).

4. Presentation Concept

This Section describes the application of the proposed presentation concept by the example of Roman Cologne. The permanent exhibition is located at the Roman Germanic Museum in Cologne and is a constituent part. The main requirements comprised the interactive exploration as well as guided interaction of the virtual 3D reconstruction. Figure 9 shows a conceptual architectural overview of the presented client-server system. The basic museum setup is shown in Figure 1. It mainly consists of the following two components:

- **Server:** The server performs real-time image synthesis of the 3D content or scene, which is then projected on a vertical surface. Depending on the scene complexity, this can be computational costly and thus requires corresponding rendering hardware.
- **Client:** The client offers the user control over the servers viewing configuration (e.g., the presentation modes) via a touch-based user interface and a 3D mouse. It displays additional information about the scene projected and is adapted to the presentation modes respectively (Fig. 2).

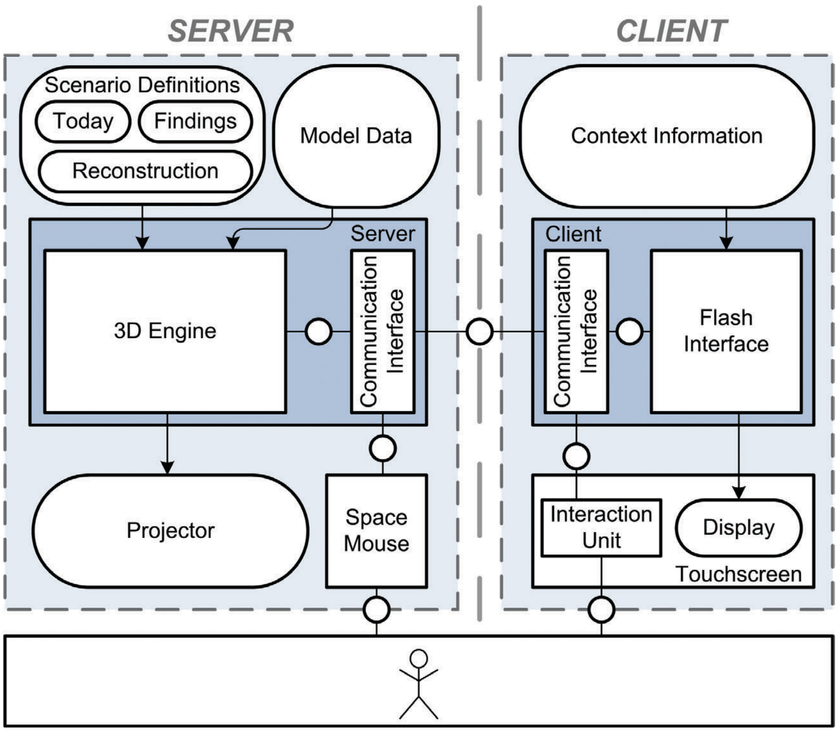


Figure 9: Conceptual overview of the client-server system used for the proposed framework.

4.1 Client/Server Approach

The presentation setup is divided into two parts: A client and a server. These two computers communicate with each other via a LAN (Fig. 9). The client is connected with a touch screen by inputech (1920x1080 pixels) based on Nextwindow technology and runs a Core2Duo 3 GHz with 2 GByte RAM and a ATI Radeon 4650 (1 GByte RAM). It is used for both, the display of context-specific information as well as terminal for controlling the server. The server runs a Core i5 750 2.66 GHz with 4 GByte RAM and a NVidia GTX 285 (2 GByte RAM) and is connected with a projector (1280x800 pixels) for displaying the 3D reconstruction on a vertical surface in front of the terminal.

The separation between server-side rendering/visualization and client-side interaction / visualization has two major advantages for systems that provide interactive installations within public places: (1) The two viewports of the server and client provides more physical space to display various types of information that can be presented with an optimal screen real-estate; (2) It enables guided interaction and navigation with the 3D virtual environment using 2D touch events and an additional 3D mouse to control the virtual camera and server state.

For the communication between the client and the server we implemented a simple text-based protocol that can be easily extended and maintained. The textual messages are exchanged via TCP/IP sockets, whereas the client controls state consistency and initiates hand-shakes and resynchronization. The following messages are exchanged:

- Client-Side: The Adobe(r) Flash(r) interface performs the initial hand-shake, transmits mode-changes, hot spot changes, the rotation angle of the panorama, as well as the blend factor for the reconstruction and the active finding. It further issues the demo mode after a defined idle time span.
- Server-Side: The rendering server confirms the execution of sent commands, and sends the position of the virtual camera at a fixed interval, as well as automatically breaks a demo mode on user interaction.

All interactive controls, such as sliders or the flow-menu element, are sampled at a user defined frequency in order to handle possible network latency and socket congestion correctly. In our implementation we achieve best result using a frequency of 70ms within LAN.

4.2 Visualization Modes

This Section describes the different presentation modes provided for the effective communication of 3D digital cultural heritage in interactive 3D virtual environments. Figure 2 exemplifies the visualization of the following three modes: the *reconstruction, comparison*, and *findings* mode.

4.2.1 Reconstruction Mode:

The visualization of possible virtual reconstructions or artifacts can be considered as main purpose for a system that communicates digital cultural heritage. It forms the basis for the remaining two presentation modes. Such reconstruction visualization is the result of numerous projects that deal with interactive 3D virtual environments. Figure 2(A) and Figure 8 show such visualization by the example of Roman Cologne (Maass & Döllner, 2008a).

4.2.2 Comparison Mode:

Based on the reconstruction mode, the comparison mode enables the comparison and dissemination of structural changes over time, i.e., between the reconstruction and today's state. We further observed, that this mode enable visitors with a local background a certain degree of entertainment.

There are several computer graphical approaches and rendering techniques of different implementation complexity to enable the image synthesis for such modes, e.g. 3D magic lenses (Bier et al., 1994) can be used to combine different geometries within a single view. Another possibility constitutes the usage of multiple viewports that contain images or screenshots using the same or similar camera configuration.

For the visualization framework of Roman Cologne, we apply a simple image-based approach that allows the side-by-side comparison of locations between the modern Cologne and the ancient version (Fig. 2 (C)). Instead of planar images, we create 360° horizontal panoramic images which are mapped onto two cylinders, each rendered using a virtual camera with an orthographic projection (Fig. 11). To navigate within this setup, the user can rotate both panoramic cameras at the same time.

4.2.3 Findings Mode:

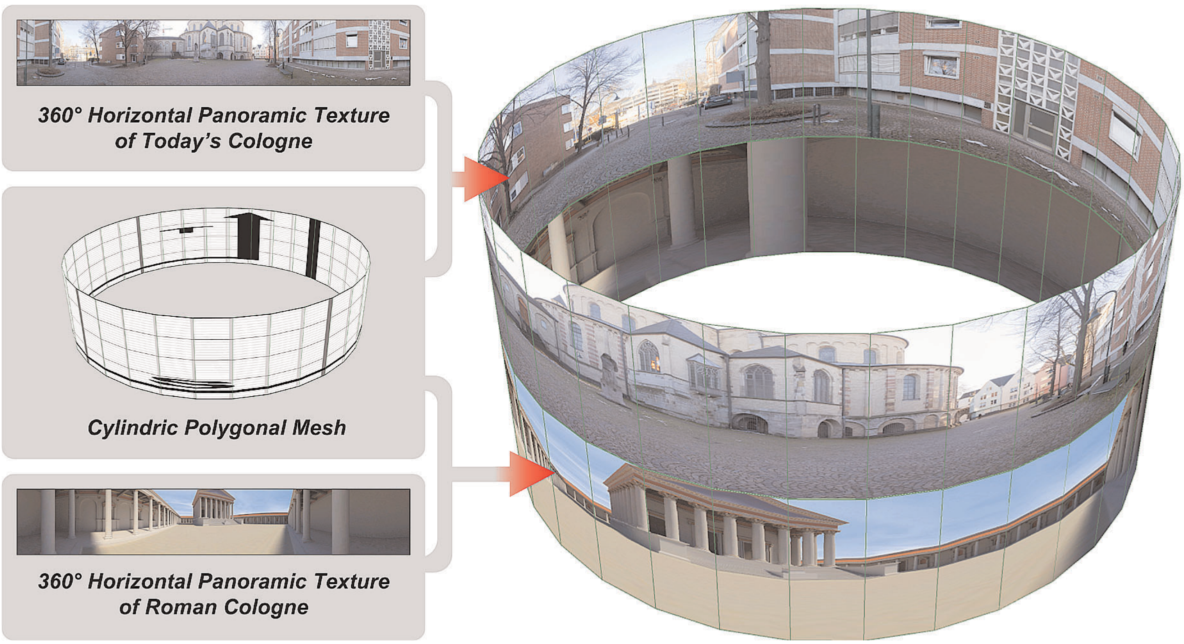


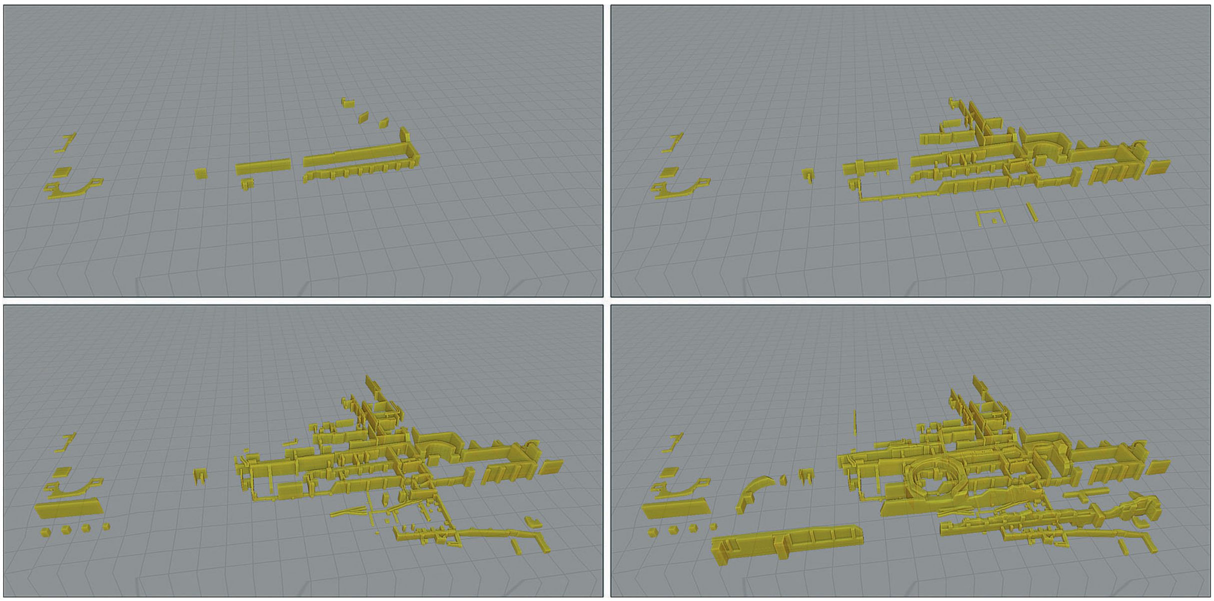
Figure 11: Components for rendering the comparison mode for Roman Cologne.

The purpose of this mode is the communication of the findings at their respective locations, which lay the basis for the actual reconstructions (Fig. 10). Our goal was to enable a user to understand the relation between artifact and proposed 3D reconstructions performed by archaeologists and designers. As an example, Figure 13 shows screenshots for the reconstruction mode of the Dionysus villa within

Roman Cologne. Approaches for the communication of finding information embedded in reconstruction visualizations have to deal with the following challenges:

1. Multiple findings for a single reconstruction require interaction concepts and rendering techniques for the selection and highlighting of an instance or a group of finding objects.
2. The system should be able to support the communication of multiple excavation stages to the user (Fig. 12).
3. The approaches require a concept that enables the communication of different reconstructions that can be derived from a set of findings (Fig. 13).

Figure 12: Example for the visualization of different excavation stages.



4. It is necessary to handle different graphical representations for a finding object: 2D photographs, hand-drawn or digital images, as well as 3D polygonal meshes or point clouds, which are obtained from laser scanning.
5. Textual descriptions are likely the medium that conveys and communicates the most context information. However, the depiction of text is limited by the available screen space and rendering quality.

Figure 13 (B) and (C) shows different reconstructions for a single set of findings. These different versions can be mutually blended with the

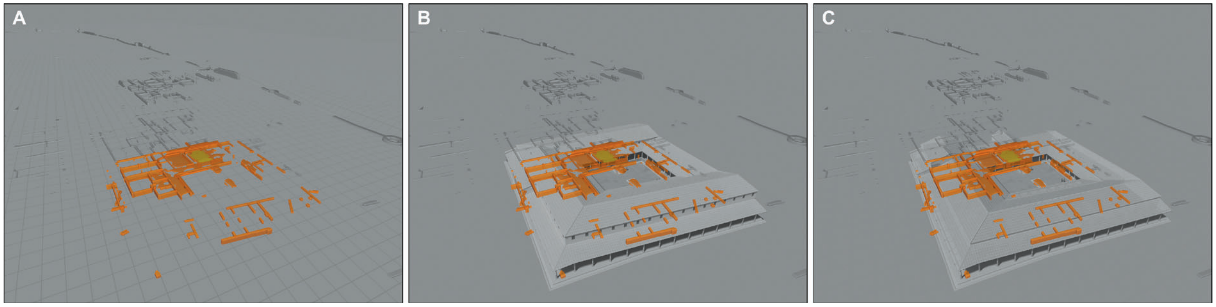


Figure 13: Finding mode of the visualization of Roman Cologne: (A) depiction and highlighting of different findings at a hot spot, (B) blend-in of a reconstruction based on Fremersdorf, and (C) the reconstruction of Precht. They differ, e.g., with respect to the number of floors.

rendering of the highlighted findings. Here, the user can control the blending factor as well as the blending speed.

We experimented with an automatic decrease of the blending values over time, but believe that this rather distracts the user. With respect to the textual descriptions of findings, we choose not to embed these within the 3D visualization (Maass & Döllner, 2008a) but depict them on an additional viewport. This functionality is described in the next section.

4.3 Supporting the User

This Section focuses on the user interface of the client (Fig. 14) and the control of server's virtual camera. As a basic functionality, the touch interface enables to switch between the three proposed presentation modes (Figure 14 (d)).

The avoidance of "getting lost situations" (Buchholz et al., 2005) in 3D virtual environments is the major goal of the proposed interaction and navigation metaphors. This comprises a trade-off between navigation aids or constraints and the total freedom to interact with the system. The orientation of the user is enabled by an overview map (Figure 14 (e)) that contains a camera glyph indicating the position and orientation of the virtual camera within the 3D scene. This map alters slightly in each presentation mode: an aerial screen shot of the complete reconstruction visualization (Figure 14 (1)(e)), a combined abstract map of the ancient and modern Cologne (Fig. 14 (2)(e)), and an aerial image of today's Cologne (Fig. 14 (3)(e)).

The 3D virtual camera and the camera glyph are synchronized. To ease the access to specific locations in the 3D virtual reconstruction, the touch interface presents a number of hot spots (Fig. 15), which can be selected from a scroll menu at the bottom. After selecting a hot spot the server's virtual camera automatically approaches it by using automatic camera control, which is an important feature for interaction within 3D virtual environments. It is applied for moving the 3D virtual camera between hot spots and between different findings in

Figure 14: Structure and organization of the client-side user interface for the reconstruction mode (1), the findings mode (2), and the comparison mode (3) by the example of Roman Cologne.

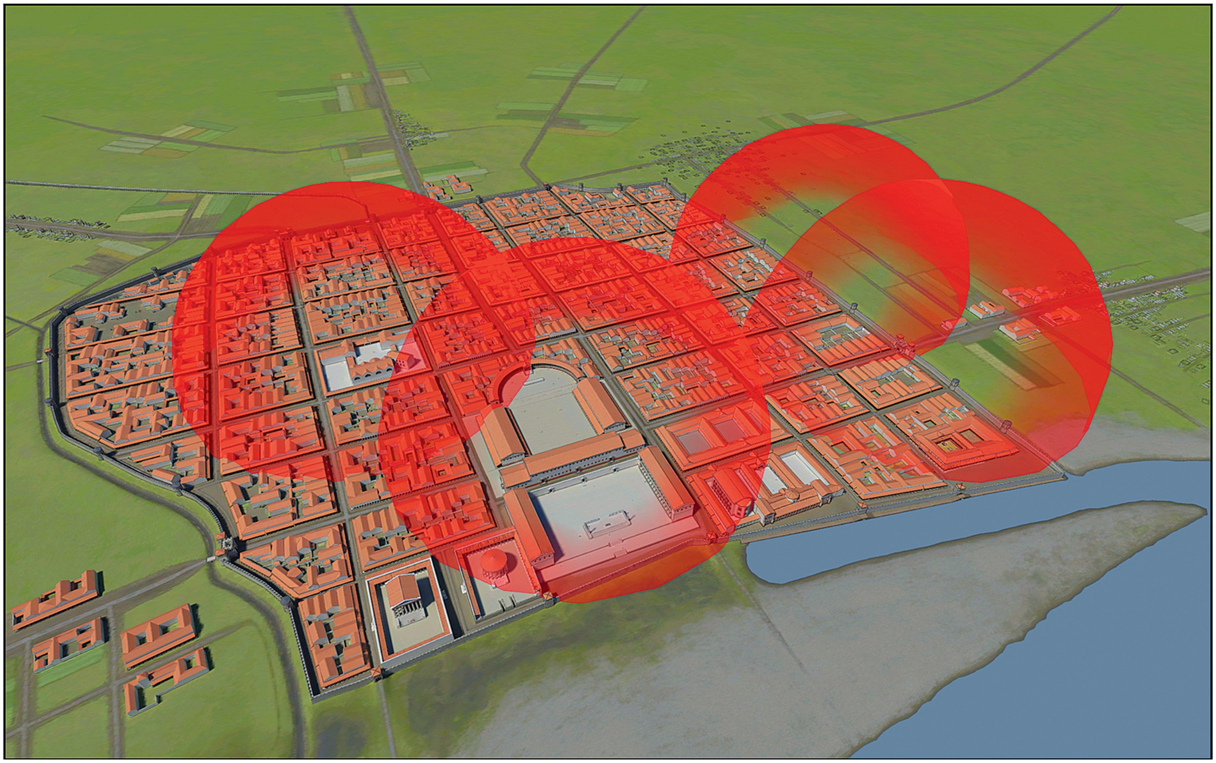


Figure 15: Visualization of the spherical navigation constraints by the example of four hot-spots.

the scene. Instead of explicitly modelling more than 100 camera paths we decided to derive these paths automatically.

Given the start and target camera settings, and the path duration, our system creates the camera path in the following manner: (1) to avoid possible collisions with buildings, the camera positions are interpolated on a parabolic path; (2) the viewing directions of the virtual camera are interpolated linearly; (3) non-linear speed is used, which results in a slow path start and end.

With respect to the interaction possibilities, we distinguish between two basic types of hot spots: (1) an overview hot spot (Fig. 14 (a)) and local hot spots (Fig. 14 (b)). The local one allows user interaction using an orbital camera model only, while the global hot spot enables free navigation of six degrees-of-freedom via a 3D mouse. If in comparison mode, the 3D mouse can be used to rotate the panorama. In addition thereto, the user can control the rotation via a slider (Fig. 14 (3) (f)) on the touch interface. If switching to the findings mode, the user faces a flow-menu from which he/her can select an active finding (Fig. 14 (2)(f)). Successively, the server moves the camera closer the findings and highlights it. A slider (Fig. 14 (2) (g)) can be used to blend-in the available reconstructions for the respective hot spot. To avoid collisions between the virtual camera and the scene objects, designers created an explicit collision model for the complete scene. In contrast to derived bounding approximations, this gives maximum control to the physics designer.

A central component for implementing the user interaction is collision detection and handling. It is used to preserve the intrusion of the virtual camera into buildings and to compute intersection points required for the orbit navigation metaphor. For implementing collision handling we use the Bullet physics engine, which is an open source software project. To increase the performance of the collision detection, we decided to use explicitly modelled collision geometry consisting of 60,672 vertices and 99,144 faces (Fig. 16). This approach has the advantage of providing maximal control to design the collision bodies, but requires a complete update of the collision model if only parts of the graphical model change.

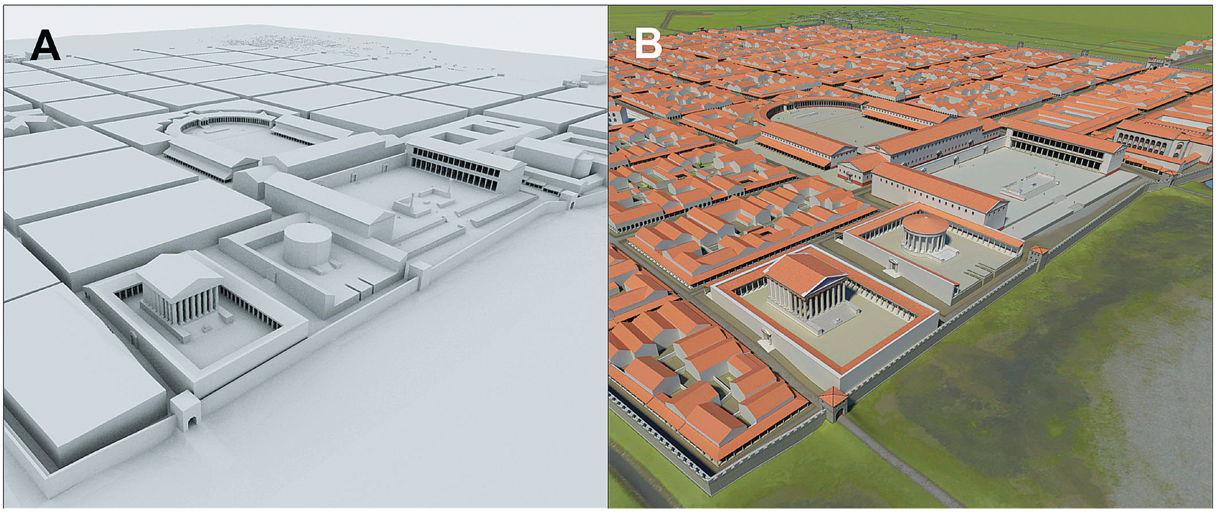


Figure 16: Comparison between the geometry representations for collision handling (A) and visualization (B).

5. Real-Time Rendering

This Section briefly describes the implementation of the previously described concepts, with the main focus on the server-side image synthesis, content management, and messaging. The client was implemented on Adobe(r) Flash(r) using object-oriented action script.

The server-side image synthesis can be performed in real-time using modern consumer graphics hardware (Akenine-Möller & Haines, 2002). Since the optimized geometric model (Table 1) fits into the video memory, we use in-core rendering techniques instead of out-of-core rendering techniques. The complete process of mesh optimization is described in (Maass et al., 2008b). We use a custom scene graph, shader programs (Kessenich, 2006) and a compositing pipeline for rendering. Therefore, each presentation mode presents a specific scene graph configuration. At loading time the geometric models are loaded and the scene graph is constructed. The client commands (Section 4) triggers the respective reconfiguration of the scene graph.

5.1 Model Optimization

All 3D models pass a number of optimization steps to maximize their real-time rendering performance (Kuehne et al., 2005; Dietrich et al., 2007). First, a polygon cleanup operator removes all obsolete data, such as unused texture coordinates, normal data, or vertex colours. Further, redundant information such as vertex duplicates or degenerated triangles are removed. Next, elements of the scene graph are reordered to minimize state switches for the graphic hardware. Afterwards, polygonal representations using the same material or texture form a group whose elements are rendered together in a sequence. The third optimization adds an index structure to the polygonal representations if a large number of triangles share the same vertex coordinates. This results in a more compact representation and reduces the allocation of the limited graphic board memory. Afterwards, indices are reordered to optimize the cache hits during the vertex processing in the graphic processing unit. In the fourth step, geometries for different objects are merged to batches to improve the rendering throughput. At least, hardware texture compression is applied for each texture to reduce the GPU memory consumption and accelerate their transfer from system memory to the graphics board. Figure 17 shows image artifacts that occur when using a lossy S3 texture compression.

5.2 Rendering Techniques

To improve the rendering performance for a scene constructed out of a number of individual 3D models, a further set of optimizations is applied. Because, illumination was pre-computed for static lighting and stored combined with material colours in the surface textures, lighting calculations are turned off during interactive rendering. Appropriate shader programs are used to minimize the processed set of vertex and fragment operations. These programs calculate only the model-view and projection transformations for each vertex, and use a single texture look-up to determine the visible colour and intensity for each drawn pixel.

To reduce the triangle count processed by the GPU per frame, we apply standard culling techniques (Akenine-Möller and Haines 2002) and introduce a simple but effective level-of-detail (LOD) mechanism. Thereby, highly-detailed parts of building geometry, e.g., capitals, are omitted during phases of intense user navigation. If the interaction with

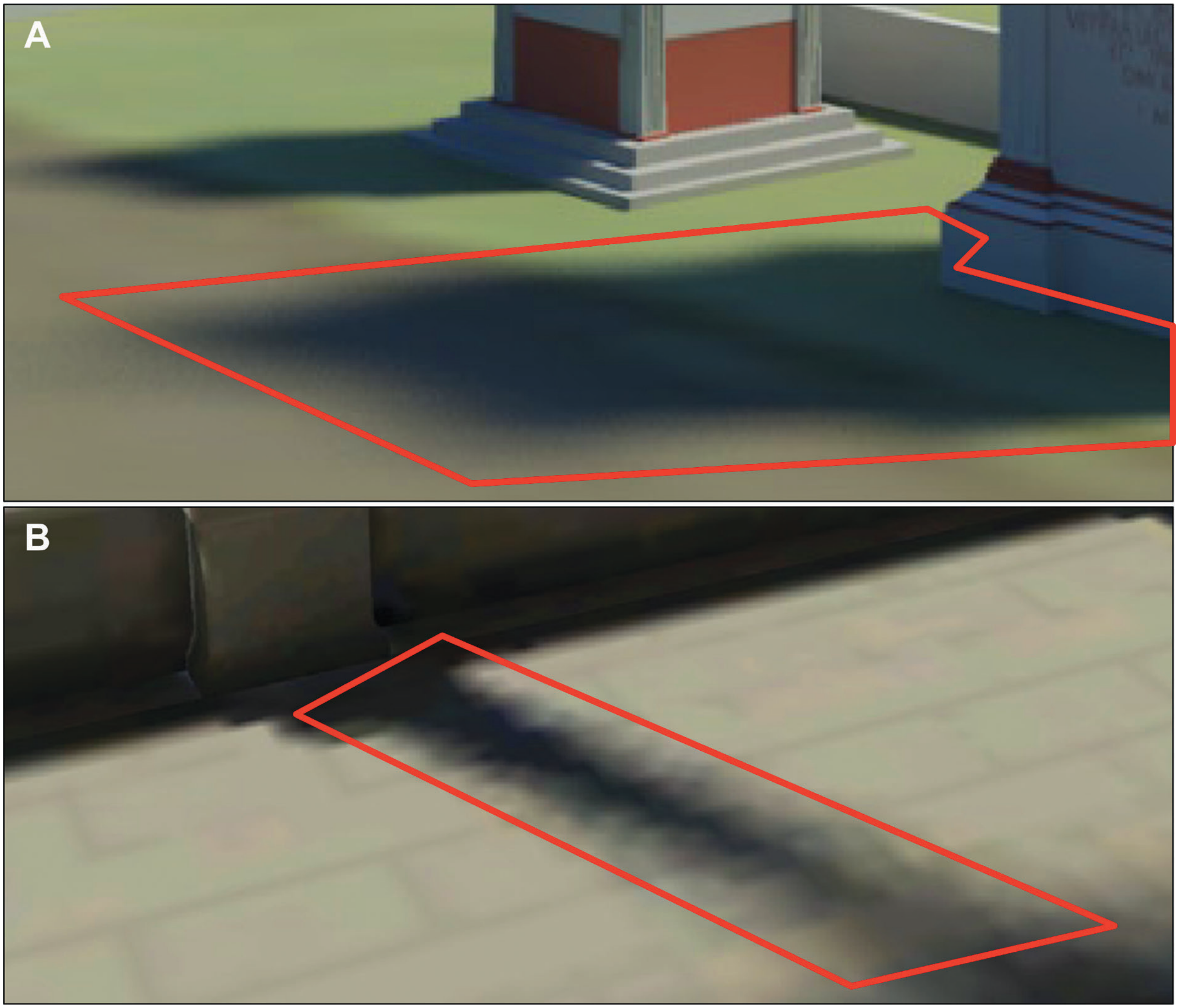


Figure 17: Image artifacts produced by the usage of texture compression (B) compared to uncompressed textures (A).

the scene stops, these elements are rendered subsequently to achieve a depiction containing all details.

5.3 Rendering Panoramas

A straight forward approach to render 360° horizontal panorama images is to project their textures onto the surface of a cylindrical projection mesh (Fig. 11), position the virtual camera in the middle and direct the view towards the vertical centre of the projection plane. In order to render panoramas of Roman Cologne in an undistorted way, the horizontal field of view (*fovx*) and vertical field of view (*fovy*) is adapted to the proportions of a panoramic texture. First, *fovy* is defined by the proportions of the cylinder. Then *fovx* is adapted to the aspect ratio of the canvas (screen) and panoramic images.

Because the camera is positioned and directed towards the vertical centre of a panorama, it is expected that the imaginary horizon of a panorama is vertically positioned on the same level. A problem occurs when the horizon of a panorama is above or below the camera's position. In this case, visually important lines that are parallel to the viewer's line of sight, e.g. roofs of buildings, become distorted. Real cameras are able to resolve this issue by using shifted lenses to correct images in perspective views with a displaced horizon.

In order to simulate a vertical shift in a visualization system, two approaches are possible. The first approach translates the camera on horizon level and applies an enlarged vertical field of view that reaches to the upper or bottom edge of the cylindrical polygonal mesh. The viewport is then clipped and stretched to fill the canvas (screen). The second approach, which we use, renders the panorama image using an asymmetric projection. In this case, the camera gets translated in vertical direction to match the image's horizon level, and the upper and lower horizontal clipping planes are shortened and stretched to the image's proportions.

5.4 Performance Evaluation

The performance of a 3D reconstruction is an important issue when a smooth and real-time experience for a user is aspired. The majority counts any application a real-time application, as soon as it renders more than 30 frames per second in average. Table 1 summarizes basic statistics for each of the three modes presented in Section 4.2.

Table 1: Statistics for the modes: reconstruction (Roman), comparison (Modern), and findings.

Mode	Vertices	Faces	Texel
Roman	16,253,173	22,242,274	1,366,818,816
Modern	136	128	12,987,912
Findings	720,954	557,286	4096

We measured the performance for the mode "Roman Cologne" on the setup described in Section 4.1. For the benchmark, we enabled view frustum, and back face culling, and disabled vertical synchronization. As basis for measuring, we used four different camera paths: Two paths that cover a bird's eye perspective and two paths that cover a pedestrian perspective. Table 2 summarizes the performance for different screen resolutions.

Table 2: Results of the performance evaluation of the reconstruction mode in frames-per-second (fps).

	Bird's Eye View			Pedestrian View		
Resolution	Avg.	Min	Max	Avg.	Min	Max
1920 x 1200	65	46	72	70	61	77
1600 x 1200	68	57	75	73	64	79
1024 x 768	72	43	81	78	70	84
800 x 600	74	40	83	80	71	85

These results show that our system setup allows rates at real-time. We furthermore observe a higher frame rate of approximately 8% in pedestrian areas. A third observation allows classifying our implementation regarding a limiting factor. As the frame rate decreases with higher resolutions, the GPU can be seen as limiting device. As a summary, our application is fill-limited, showing an increase of 15% when using a resolution of 800x600 pixels instead of 1920x1200 pixels (Full HD).

6. Conclusions and Future Work

This paper presents a concept and implementation for the interactive communication of digital cultural heritage in public spaces by the example of the research project Colonia3D. The proposed concept and system makes use of a client-server architecture, consisting of a 3D real-time rendering server and 2D touch sensitive user-interface to enable guided user exploration of a 3D virtual environment and knowledge communication. We generalized the approach towards a visualization tool for digital cultural heritage. The system, installed as permanent exhibition in the Romano-Germanic-Museum in Cologne, turns out to be a success. The established content creation process as well as the chosen data formats proven themselves in practice. The developed framework allows the interactive exploration of the virtual reconstructed Roman Cologne. Despite museum systems, high-detailed virtual 3D reconstructions can have various areas of applications. For instance, they can be used to reproduce 3D scale models or can serve as scenery for movies.

For the final version, the high-detail virtual 3D reconstructions partially required multiple iterations and revisions by archaeologists and designers. The evaluation of the proposed system comprises two main steps: a test phase and a reviewing phase. During the test phase, the systems setup is tested thoroughly off-line. This includes the tuning of sensitivity parameters of the input device and the physics engine. In the reviewing phase, the system is installed in the Roman-German Museum and is tested by staff and visitors. The results of that phase (one month) are then incorporated in the system. The observations during that phase basically yield positive response by the users, even if only a single user can interact with the system, while others are watching and waiting. We observed that the comparison mode was very popular among most of the visitors. Further, the inclusion of scale elements (e.g., virtual characters) helps the user to estimate the size of the depicted structures. Furthermore, it is important to acquire robust and durable rendering and interaction hardware for a public setup to prevent premature wear out, which can cause downtime of the system. We believe that interactive systems in the area of digital cultural heritage have the potential to become important tools for education and training, as well as facilitate further applications in the fields of education, tourism, and restoration.

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References

Akenine-Möller, T. & Haines, E., 2002. *Real-Time Rendering*, 2nd edition, A K Peters Ltd., Wellesley, Mass.

Almagro, A. (et al.), 2006. *The Alcazar of Seville in the 14th Century*, VAST 2006, pp.15-22.

Arnaud, R. & Barnes, M. C., 2006. *Collada - Sailing the Gulf of 3D Digital Content Creation*. A.K. Peters Ltd., Wesley Mass

Bergamasco, M. (et al.), 2002. *Tactual Exploration in Cultural Heritage.* XIV Round Table Computer-Aided Egyptology, Pisa, Italy.

Bier, E. (et al.), 1994. *Toolglass and Magic Lenses: The see-Through Interface*: CHI 1994, ACM Press, New York, NY, USA.

Boland, P. & Johnson, C. 1996. *Archaeology as computer visualization: 'Virtual tours' of Dudley Castle c. 1550*. Imaging the Past. Electronic Imaging and Computer Graphics in museums and archaeology, Higgins T. (et al., Ed.), pp. 227-234.

Buchholz, H. (et al.), 2005. *Smart and Physically-Based Navigation in 3D Geovirtual Environments*. 9th International Conference on Information Visualization, IEEE Computer Society Press, pp. 629–635.

Campos, P. (et al.), 2009, *Interactivity for museums: Designing and comparing sensor-based installations.* INTERACT 2009, Springer, pp. 612-615.

Carrozzino, M. (et al.). 2008. *The virtual museum of sculpture.* DIMEA '08, vol. 349, ACM, New York, NY, pp. 100-106.

Christou, C. (et al.), 2006. *A versatile large-scale multimodal VR system for cultural heritage visualization.* VRST '06, ACM, New York, NY, pp. 133-140.

Cruz-Neira, C. (et al.), 1993. *Surround-screen projection-based virtual reality: the design and implementation of the CAVE.* SIGGRAPH '93. ACM, New York, NY, pp. 135-142.

Debevec, P. E., 2005. Making "The Parthenon", *Invited paper of VAST 2005*, http://www.debevec.org/Parthenon/debevec-vast2005-parthenon.pdf, Pisa, Italy (accessed 28 Sep. 2011).

DeLeon, V. & Berry, R. Jr. 2000. *Bringing VR to the Desktop: Are You Game?.* IEEE MultiMedia 7(2), pp. 68-72.

Dietrich, A. (et al.), 2007. *Massive-Model Rendering Techniques, IEEE Computer Graphics and Applications* 27(6), pp. 20-34.

Foley, J. D. (et al.), 1990. *Computer Graphics: Principles and Practice*, 2nd ed., Addison-Wesley Professional.

Gonçalves, A. (et al.), 2009. *High dynamic range — a gateway for predictive ancient lighting.* JOCCH 2(1), pp. 1-20.

Gooch, B. & Gooch, A. A., 2001. *Non-Photorealistic Rendering*, AK-Peters.

Gutierrez, D. (et al.), 2008. *Modeling light scattering for virtual heritage.* JOCCH 1(2), pp. 8:1-8:15.

Heim, M. 1997. *Virtual Realism*, 1st ed., Oxford University Press, New York, NY, USA

Irmler, B., 2004. *Rekonstruktion einer Porticusordnung an der Rheinseite in Köln.* Kölner Jahrbuch 37, Gebr. Mann Verlag, Berlin, pp. 77–102.

Kessenich, J., 2006. *The OpenGL Shading Language*, Version: 1.20 Document Revision: 8, Manual.

Khronos Group, 2008. *Collada 3D Asset Exchange Format.* http://www.khronos.org/collada/ (accessed 28 Sep. 2011).

Kuchar R. (et al.), 2007. *Photorealistic Real-Time Visualization of Cultural Heritage: A Case Study of Friedrichsburg Castle in Germany*, Eurographics Cultural Heritage Papers, pp. 9-16.

Kuehne, B. (et al.), 2005. *Performance OpenGL: Platform Independent Techniques.* ACM SIGGRAPH 2005 Courses, J. Fujii (Ed.), ACM, New York, NY.

Laycock, R. G. (et al.), 2008. *Exploring cultural heritage sites through space and time.* JOCCH, 1(2), pp. 1-15.

Lepouras, G. (et al.), 2004. *Real exhibitions in a virtual museum.* Virtual Reality 7(2), pp. 120-128.

Lotte F. (et al.), 2010. *Exploring Large Virtual Environments by Thoughts using a Brain-Computer Interface based on Motor Imagery and High-Level Commands.* Presence Teleoperators and Virtual Environments 19(1), pp. 54-70.

Luft, T. (et al.), 2006. *Image enhancement by unsharp masking the depth buffer*, SIGGRAPH 2006, pp. 1206-1213.

Lutz, B. & Weintke, M., 1999. *Virtual dunhuang cave; a cave within a CAVE.* Eurographics 1999, Computer Graphics Forum 18(3), pp. 257-263.

Maass, S. & Döllner, J., 2008a. *Seamless Integration of Labels into Interactive Virtual 3D Environments Using Parameterized Hulls*, 4th International Symposium on Computational Aesthetics in Graphics, Lisbon, pp. 33-40.

Maass, S. (et al.), 2008b. *Techniques For The Interactive Exploration Of High-Detail 3D Building Reconstruction Using The Example Of Roman Cologne*. VSMM 2008: (M. Ioannides et al., Eds.), Archaeolingua, pp. 223–229.

Magnenat-Thalmann, N. (et al.), 2006. *Real-time animation of ancient Roman sites*. GRAPHITE 2006, ACM, New York, NY, pp. 19-30.

Mazuryk, T. & Gervautz, M. 1996. *Virtual Reality History, Applications, Technology and Future*. Technical Report, TR-186-2-96-06, Institute of Computer Graphics and Algorithms, Vienna University of Technology.

Michael, D. (et al.), 2010. *Comparative study of interactive systems in a museum*. EuroMed 2010, Ioannides M. (Ed.), Springer, Berlin-Heidelberg, pp. 250-261.

Museums Association. *Code of Ethics for Museums.* http://www.museumsassociation.org/ethics/code-of-ethics (accessed 30 Sep. 2011).

Papagiannakis, G. (et al.), 2001. *Real-Time Photo Realistic Simulation of Complex Heritage Edifices*. VSMM 2001. IEEE Computer Society, Washington, DC, pp. 218-227.

Papagiannakis, G. (et al.), 2005. *Mixing virtual and real scenes in the site of ancient Pompeii.* Computer Animation & Virtual Worlds 16(2), pp. 11-24.

Petridis, P. (et al.), 2005. *Exploring and Interacting with Virtual Museums*. CAA 2005, Figueiredo, A. & Leite Velho, G. (Eds.).

Pujol Tost, L. & Economou, M., 2009a. *Exploring the Suitability of Virtual Reality Interactivity for Exhibitions Through An Integrated Evaluation: the Case of the Ename Museum,* Online Interanational Museology Journal 4, pp. 84-97.

Pujol Tost, L. & Economou, M., 2009b. *Worth a Thousand Words? The Usefulness of Immersive Virtual Reality for Learning in Cultural Heritage Settings.* International Journal of Architectural Computing, 7(1), pp. 157-176.

Remondino F. (et al.), 2009. *3D virtual reconstruction and visualization of complex architectures – the 3D-Arch project.* International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 38(5/W1), on CD-Rom.

Santos, L. (et al.), 2006. *High Fidelity Walkthroughs in Archaeology Sites*, VAST 2006, Pisa, Italy, pp. 453-458.

Song, M. (et al.), 2003. *Interacting with the virtually recreated Peranakans*. GRAPHITE 2003, ACM, New York, NY, pp. 223-228.

Trapp, M. & Döllner, J., 2008. *A Generalization Approach for 3D Viewing Deformations of Single-Center Projections*. GRAPP 2008, José Braz (et al., Eds.), INSTICC Press, pp. 162–170.

Ulicny, B. & Thalmann, D., 2002. *Crowd simulation for virtual heritage*. Proceedings of First International Workshop on 3D Virtual Heritage, pp. 28–32.

Weibel, R. & Heller, M., 1991. *Digital terrain modelling*, Geographical Information Systems: Principles and Applications, D.J. Maguire (Ed.), Longman Scientific & Technical, pp. 17–90.