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Visualizing Digital Architectural Data for Heritage Education

Chase J. Brown, Siyuan Yao; University of Notre Dame
Xiaoyun Zhang; Massachusetts Institute of Technology
Chad J. Brown, John B. Caven, Krupali U. Krusche, Chaoli Wang; University of Notre Dame

Abstract

This paper presents an online tool for heritage education that visualizes large-scale digital architectural data of the Roman Forum in Rome, Italy. Leveraging Potree and WebGL, the tool enables the web-based visualization of registered point cloud data as the base framework for the context and the reconstructed geometries with mesh models wrapped with images of standing monuments as the focus. The tool lets users overview the entire heritage site and examine the details of the fine monument. The 3D reconstructed mesh and surface models allow users to explore and study the site as it exists today in relation to its reconstructed views. The site is tagged with historical information and imagery for further referencing. The paper concludes with a report on visualization results and an ad-hoc evaluation provided by domain experts.

Introduction

As part of the Digital Historic Architectural Research and Material Analysis (DHARMA) [4] team at the University of Notre Dame, this paper presents our recent progress in developing a visualization tool for heritage education on the 2900 years old site of the Roman Forum in Rome, Italy. Our primary motivation is to provide students and teachers easy access to large datasets of 3D laser scans collected over multiple years of a survey of individual historical monuments and registered together to create a comprehensive first-time visualization of this historic site. These are overlaid with 3D reconstructions and detailed mesh models to further understand the site monuments and their transformation. The tool will complement textbooks and other teaching materials, allowing students to explore the monuments in 3D space in addition to 2D photos and drawings - all original sources for data collected on-site. Our secondary motivation is to produce a digital web-based archive for DHARMA's ongoing work on the Roman Forum and other World Heritage sites, like the Taj Mahal, Mumbai, and Vatican City. The archive can thus serve as a single source for all polished datasets and reconstructed models created by our team as research continues.

Through field documentation since 2010, the digitally scanned data of the Roman Forum encompasses monuments between the area of Capitoline Hill and Colosseum. This research includes seven monuments (the five ancient temples and two triumphal arches) and their surroundings. The DHARMA team organized four groups for the site survey: *digital survey*, *traditional survey*, *photogrammetry*, and *photography* [17]. The digital survey group employed multiple long-range Leica Geosystems scanners and achieved an accuracy of up to 4mm in resolution at distances of up to 50m [20]. Individual scan location was marked and referenced in 3D, which yielded the point cloud data used in this work. In contrast, the traditional survey group applied time-honored techniques of hand measuring and field notes. In addition, the photogrammetry group captured 2D elevations of the monuments. Finally, a photography group leveraged a high dynamic range (HDR) GigaPan System EPIC Pro robotic camera mount and Nikon professional D5 digital camera to capture ultra-high resolution images. GigaPan photos and hand-measured drawings were referenced in the digital modeling process for speculating reconstruction details, such as cornices and inscriptions.

In 2018, research was conducted with the auspices of creating reconstructed wireframe 3D models using Rhino 3D [9] based on the survey data measurement of the Forum. In 2020, the team was challenged to opt for web deployment and create a visualization tool, eliminating the need for software download and installation. The challenge was the heaviness of the dataset. The primary point cloud dataset for our demonstration of the Roman forum contains 328 million points. The data was originally stored in an ASCII XYZirgb for human readability during the initial stages of work until converted into BIN for uploading to the server hosting our application. The issue of uploading large datasets was resolved by creating a tool mainly built using Potree [28], an open-source WebGL-based point cloud renderer. Depending on the power of the user's device, Potree dynamically renders only a fraction of the available point cloud data. To enhance the readability of the dataset, we generated coarse and fine individual mesh and image textured models of the monuments. We rendered them using WebGL, enabling users to view the standing monuments in their ruinous form of 3D structures. In addition, the reconstructed wireframe models were layered on the same monument surfaces along with viewable text and photos for a comprehensive understanding of the site. The tool was deployed in February 2022 at a compendium book release event in Curia at the Roman Forum. Users tested the tool at the event to explore its viability, as detailed further in the paper.

Related Work

Cultural heritage sites have been well studied and documented for centuries using various graphic and visualization techniques. For example, Owen et al. [26] outlined technologies used in cultural heritage to direct future research in this field. Rodrigues et al. [27] proposed a domain-specific modeling method for the automatic reconstruction of virtual heritage sites, in particular Roman structures. Guidi et al. [18] developed a multi-resolution technique for 3D modeling the Roman Forum. Bettio et al. [12] presented a real-time framework for the point-based rendering of large 3D scanned models using graphics hardware. Micoli et al. [23] described a multi-scale and interdisciplinary cultural heritage inspection approach for validating historical hypotheses, incorporating 3D laser scanning, orthoimages, historical studies, and complementary information. Bernardes et al. [11] considered three visualization methods (oblique lighting, interpretation-free alignments, and scalar-based segmentation) for 3D archaeological data and evaluated their usability.

Researchers have developed various solutions for digital reconstruction, information management, and visual exploration of historical buildings or heritage sites around the world, such as India [15], China [21], Italy [29], Algeria [32], Poland [25], and Central Asia [24]. Based on the open-source photogrammetry pipeline, e Sá et al. [16] presented a framework for documenting open cultural heritage assets considering different phases, including identification, data acquisition, processing, evaluation, and access. Windhager et al. [30] provided an introductory survey on the visualization of cultural heritage collection data. Exemplary visualization or visual analytics systems include Living Liquid for museum visitors [22], Vis4Heritage [31] for grotto wall painting degradations, VAiRoma [14] for sense-making of Roman history, and Reading Traces [13] for scalable and elastic visualizations of personal reading traces.

Our work focuses on heritage education, which significantly differs from the above works. In this sense, our work is close to that of Montusiewicz and Milosz [25], which designed a two-player computerized board game for recognizing historical architectures and their positions. However, while our end goal is similar to CyArk's Monumental Ideas [7], our visualization is based on Potree and WebGL instead of Unity3D, which could be too heavy for end-users to run educational tools on the web. Unity3D, to date, has shown only an individual mesh model on the web interface, whereas Potree permits the uploading of larger datasets of multiple varieties of size, scale, and software base. Potree also created usability and easy navigation of the data with smooth movement not available in other software. Users start with an overview of the Roman Forum rendered in the point cloud. Monuments of interest are explorable targets with labels that guide them to "zoom" into the details.

Design Considerations

We laid out the following design considerations for implementing the visualization tool through multiple rounds of discussion among the DHARMA team members. **C1: web deployment.** The visualization tool should run on web browsers, making it easy for users to visit without explicit download or installation and for us to update without considering the variation across different operating systems. **C2: interactivity.** The tool should support interactive exploration of the scene and monument models across desktop, laptop, and smartphone users. **C3: quality.** To maximize the user experience, we should pay attention to model details and rendering effects, maintaining a good balance between interactivity, accuracy, and quality. **C4: multimodality.** To allow students to examine the monuments in various forms, we should provide different data modalities for a comprehensive investigation. **C5: multimedia.** To enrich the educational experience, we should integrate diverse information, including point cloud, geometry, text, photo, animation, etc., into the tool. **C6: education.** We incorporate historical and archaeological information into model reconstruction and design lessons for monuments by considering that the tool is for educational purposes.

Data Processing

We processed the point cloud data by registering and aligning scans through the aid of Leica GeoSystems Cyclone software [6]. Potree maintains a conversion software that takes our point cloud scans and converts them into an octree format, supporting level-of-detail rendering (**C2**). The scanner-output data are compressed at about 4:1 before landing on the web interface. Furthermore, we built coarse and fine models of the monuments for closer examination (**C4**). For this purpose, the individual monument models are isolated from the larger registration and cleaned up before use in CloudCompare [3]. We then combined the deliverables with the previously registered data placed in Potree. Finally, these individual coarse models of standing monuments are laid over with the digitally reconstructed fine models of the same (**C4**). In the end, we created the cumulative visual impact of a high-resolution display of the 3D model of the whole Roman Forum on a web interface (**C1, C3**).

(a) (b)

Figure 1. *(a) and (b) show the low-poly and original models of Temple of Vespasian and Titus.*

Creation of Coarse Models. We created coarse mesh models from the point cloud data using CloudCompare. We used a mesh generation method [19] to build watertight high-resolution mesh models of the monuments. However, the generated models are usually quite large, ranging from 100MB to more than 1GB depending on the density of point clouds. Considering the web constraints, we converted the original models to low-poly models in sizes around 2.5% to 50% of the original ones using the "decimate" modifier in Blender [1] (**C2**). For example, the size of Temple of Vespasian and Titus is reduced from 446MB to 11MB. Figure 1 shows the rendering of the temple in the low-poly and original versions. The original models are used for baking the normal map and color texture for the low-poly models to maintain equivalent visual quality. The normal map and color texture are in the resolution of 4K or even 8K. These textures are also small in size. For instance, the size of the 4K normal map for Temple of Vespasian and Titus is 3MB, and the size of the 4K color texture is 2MB. To emphasize the details of the monuments, such as sculptures and corrosion, we leveraged environment maps in the rendering to generate an indirect illumination effect. With these techniques, we provided high-fidelity visualization of the monuments on the web with low demand on network speed and

Figure 2. *The aerial view of our visualization of the Roman Forum shows the point cloud data overlaid with a Cesium global map, which provides contextual information. The control panel is on the top-left side.*

graphics processing (**C3**).

Digital Reconstruction of Fine Models. Besides coarse models, we reconstructed fine models manually using Rhino 3D, integrating digital, historical, and archival documentation and learned traditions in classical architectural design (**C4**). We started reconstructing digital models of several monuments in the Roman Forum based on first-hand scan data and hand-measured drawings from fieldwork completed by the DHARMA team in 2010, 2012, and 2015. We were able to produce a high-resolution aerial view of the site spanning from Temple of Concord and Temple of Vespasian and Titus to Temple of Caesar and Arch of Augustus. After identifying building footprints and remaining structures in the aerial scan data, we overlaid a survey drawing of Giacomo Boni to compare multiple locations and the current context of several prominent monuments such as Temple of Saturn and Arch of Septimius Severus [17]. We built these digital models by referring both to the scan and archaeological documentation of the Roman Forum and artistic or measured renderings of building elevation and sections provided by architectural scholars (**C3, C6**). We established our approach to digital reconstruction in a greater context. Specifically, we considered not only the existing and historical conditions of each monument in its context but also the design principles of classical architecture, such as perspective view and building hierarchy (**C3, C6**). The goal is to further evaluate potential reconstruction details, especially on spaces and structures that connect two monuments. This incorporates concerns related to the precise adaptation of standing ruins as existing on-site. For example, we proposed a different solution to a potential portico-like structure between Basilica Julia and Temple of Caesar. Referring to our point-cloud model, we compared the remains of the portico-like structure with reconstruction drawings of building plans and elevations [5]. We found that the distance between the proposed southern entrance to the basilica and the northern wall of the temple is more likely to accommodate a single opening. This design of either an arch or a portico creates a consistent progression of space on Via Sacra towards Arch of Septimius Severus and frames perspective views to Temple of Antoninus and Faustina.

Data Visualization

Figure 2 shows an overview of our visualization tool. We layered Potree rendering of the point cloud data on top of a Cesium global map [2] which uses Bing satellite imagery. This allows the user to view the point cloud and associated mesh data within the context of their geographic locations. Figure 3 displays a zoom-in view of the point cloud data. We provided a simplified control panel for user settings on the top-left side. Users can set the view (i.e., toggling coarse mesh, fine reconstruction, and point cloud) (**C4**), measure the distance, choose a different lesson about a monument (**C6**), and adjust the quality of point cloud rendered (low, medium, high) for quality and speed tradeoff (**C2**). Monuments of interest are tagged with labels, which guide users in entering the associated lesson (**C5**). Upon clicking on a label, the tool automatically zooms into the corresponding monument for further exploration with additional text and photos (**C5**). Finally, we provide two buttons for easy navigation control. Users can go back to the previous view by clicking on the "Return" button or reset the default view by clicking on the "Reset" button.

Our visualization tool uses Three.js [10] to render the polygon file format (PLY) meshes (**C1**). Meanwhile, Potree is used to render the octree point cloud data (**C1**). Because Three.js and Potree are both built on WebGL, we can create one scene within

Figure 3. *A zoom-in view of the point cloud data rendered in high quality.*

the same renderer. This treatment allows users to display all three different data representations (point cloud, coarse mesh model, fine model) in the same view for convenient referencing. Figure 4 shows such an example. Note that Potree provides the ability to scale the number of points being rendered at one time. It also dynamically decides which nodes in the octree point cloud data structure should be rendered to provide the best visual experience. Therefore, our tool will not waste computing resources on rendering data that are not in the current camera view or are occluded by other point cloud data in 3D.

We applied uniform hemisphere lighting across the scene and a point light coming from the viewing direction. Applying the lighting effect after the models are generated allows them to maintain similar lighting and shading even when the scans and images used for texturing were collected on different dates (between 2010 and 2015) and times (morning, afternoon, and evening light) (**C3**).

Figure 5 shows labels tagged to Temple of Saturn. These labels enable users to focus on specific features of a monument (i.e., the architrave shown in Figure 6). These labels maintain the same coordinates and operations when viewing all three data types and bring up text, photos, animations, and other teaching materials (**C5**).

Evaluation and Discussion

Ad-hoc Evaluation. Our visualization tool has demonstrated its potential to facilitate students' understanding of large-scale architectural monuments. Two domain experts of the DHARMA team used our tool in several 10-minute sessions and provided the following feedback. Overall, the tool is highly valuable for archaeology and architecture folks. The tool lets them easily interact with the full model for a complex site with multiple large monuments. The granulation of the datasets causes the model to look "sparkly" at low resolution and is less visually pleasing to them. The clickable labels on each monument effectively bring the focus from the entire scene to the individual monument. It is also comparatively easy to transit from coarse to fine models. A measuring tool is also available, which could be enhanced for proper use. It is desirable to provide the "back" button to support better user navigation. These are correctable deficiencies in the subsequent tool updates. The rendering was visible and useable on multiple laptops and smartphones on early tests. Various target users (including K-12 age groups, teachers, World Heritage and Cultural Heritage management teams, archaeologists, historians, art historians, scientists, and architects) can benefit from this easily accessible platform that does not require software download or high-end computing power.

Discussion. A multi-modal representation of a cluster of architectural monuments on an urban scale is one of the essential aspects of our tool. Earlier visualization tools provided less or no context to historical buildings or artificially added digital environments to compensate for the lack of on-site documentation. Our tool starts with an urban setting and gradually shrinks the presentation scale down by allocating individual monuments and overlaying digital reconstruction, analytical drawings, and photographs to enrich the acquirable information into architectural details. One student who tested our tool confirmed that seeing a greater context for historical monuments such as the Roman Forum is crucial for her to perceive the building environment and urban culture. With our tool, she could imagine how people might use the space around a monument and how they approach and exit the temples. The combined use of coarse and fine models and line-drawing works is visually similar to architectural students' design process: they look at photographs and diagrams of prece-

Figure 4. *The reconstructed fine model of Temple of Saturn and the coarse mesh model with a wireframe of Temple of Vespasian and Titus. Both models are overlaid over the point cloud as the context.*

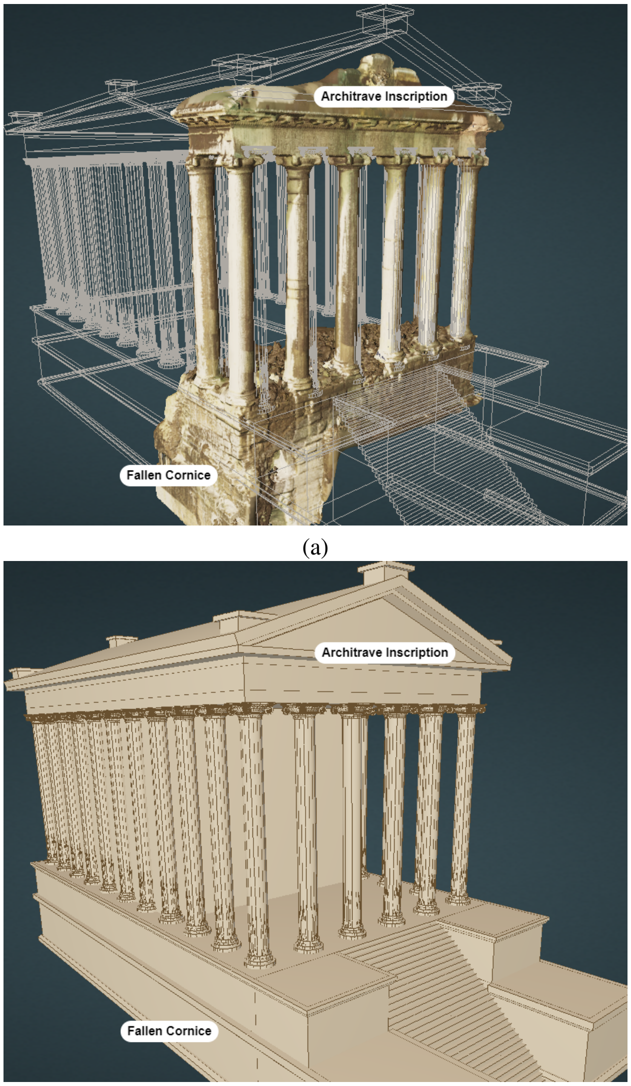
dents and conjure line drawings and overlays either in their minds or by drawing on paper. It is crucial for educators to stimulate these composite senses of visual activities. Our tool, therefore, facilitates a starting point for constructing such an environment.

Nevertheless, our tool has limitations in establishing such a composite environment in its early development. As our digital reconstruction only includes the primary geometry of the monuments in the PLY format, it only allows a limited representation of reconstruction. For example, in the overlay of the existing reconstruction shown in Figure 5, we could only present a wireframe rendering of the digital model. Furthermore, due to overlapping lines, it is tough for students to understand the volumetric information and spatial relationships for any monument of fine detail and complex architectural composition. Therefore, to obtain a cleaner and more architectural rendering of the temple, we should omit lines that are invisible from any perspective view. Our successive work will add rendered textures based on our data capture of each monument's color and weathering condition to allow a more holistic visualization of the reconstruction. In addition, we expect to assign custom materials based on GigaPan photos to each monument and provide more graphic options, such as lighting and transparency, to enhance the reading of the solidity of our digital models.

DHARMA is a team of faculty, graduate, and undergraduate students who put hours and hours behind each text, archival research, field hand measure drawings, surveying with laser and HDR digital documentation, and painstakingly created line-drawing plates as visible in the École des Beaux-Arts tradition. Our team uses both traditional and innovative documentation methods of World Heritage Sites. Since 2010, the team has undertaken a project at the Roman Forum to measure, document, and draw large areas of the historic site. Employing the latest optical technology, a high-definition surveying laser and Gigapan, the team was able to document the existing state of the site in unprecedented detail. Traditional methods of hand-measuring were conducted to capture the data gathered through this digital technique. In a continuing partnership with the Parco archeologico del Colosseo (P.AR.Co) [8], the DHARMA team has produced detailed architectural drawings, digital models, and high-resolution panoramic photographs, with techniques demonstrated in our latest book [17]. Because the DHARMA team is privileged to be multidisciplinary, we can provide our visualization platform with supplementary text and photo information currently only available on our platform. These supplemental materials have come from multiple occasions of field research and our partnership with P.AR.Co. This web-interface visualization tool allows all the relevant datasets to be visible for the first time in a coherent manner. These with reduced files are now open and accessible to various users to interact in real time.

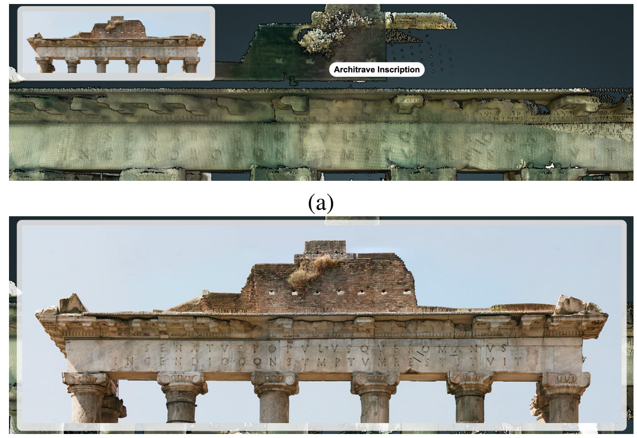
Conclusions and Future Work

We have presented our work of creating a visualization tool on a web interface with large datasets of digital architectures of the Roman Forum and discussed its potential for heritage education. Our web-based solution lets users explore the data and associated information by carefully prioritizing the large point cloud



(a) (b)

Figure 5. *(a) and (b) show the coarse mesh model with a wireframe and the reconstruction of the fine model of Temple of Saturn.*



(a) (b)

Figure 6. *(a) shows a supplementary HDR GigaPan photo of the architrave of Temple of Saturn. (b) shows the enlarged view of the photo for a close-up examination.*

data and derived geometric meshes and reconstructed models.

Furthermore, we are building an additional tool for educators to customize lessons and evaluate student understanding through interactive assessments. This tool will allow educators and users without prior geospatial visualization experience to better customize the material to fit their needs. The user will be able to adjust the content of the text, images, assessments, and other available features based on the focus of the application. The tool will be built using a modern web framework to provide the foundation for future work. In addition, we are migrating our current work to Amazon Web Services to scaffold a scalable architecture and enable users to upload their own geospatial data and construct new scenes.

In the future, we will improve the tool based on expert feedback and create remaining lessons to cover all seven monuments. We will also populate the interface with more photos and text to enrich the educational material and design automatic tours for novices to quickly grasp information with a reduced interaction requirement. In the long run, we will apply the same visualization platform to other digital data collected by the DHARMA team, including renowned World Heritage Sites like the Taj Mahal, the historic city of Mumbai, India, and the Vatican City.

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Author Biography

Chase J. Brown *received his B.S. degree in computer science from the University of Notre Dame in 2022. Currently, he is a software engineer at the Boeing Company.*

Siyuan Yao *is a Ph.D. student in the Department of Computer Science and Engineering at the University of Notre Dame. His main research interest is data visualization.*

Xiaoyun Zhang *is a SMArchS student in Computation at the Department of Architecture, Massachusetts Institute of Technology. She has researched Traditional East Asian Architecture and its design philosophies compared to the Greco-Roman tradition. She has been working with the DHARMA team, where digital documentation, preservation, and visualization of World Heritage Sites have been the primary focus.*

Chad J. Brown *is an undergraduate student in the Department of Computer Science and Engineering at the University of Notre Dame.*

John B. Caven *is an undergraduate student in the Department of Computer Science and Engineering at the University of Notre Dame.*

Krupali U. Krusche *is an associate professor in the School of Architecture at the University of Notre Dame. She received a Ph.D. degree in urban preservation from the Technical University of Dresden in Germany in 2017. Since 2007, she has founded and directed DHARMA research specializing in 3D documentation of World Heritage Sites using advanced mapping techniques.*

Chaoli Wang *is a professor in the Department of Computer Science and Engineering at the University of Notre Dame. He received a Ph.D. degree in computer and information science from The Ohio State University in 2006. Dr. Wang's primary research interest is data visualization, particularly in time-varying multivariate data visualization, flow visualization, information-theoretic algorithms, graph-based techniques, and deep learning solutions for big data analytics.*