

Research Challenges for Digital Archives of 3D Cultural Heritage Models

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The increasing creation of 3D cultural heritage models has resulted in a need for the establishment of centralized digital archives. We advocate open repositories of scientifically authenticated 3D models based on the example of traditional scholarly journals, with standard mechanisms for preservation, peer review, publication, updating, and dissemination of the 3D models. However, fully realizing this vision will require addressing a number of related research challenges.

In this article, we first give a brief background of the virtual heritage discipline, and characterize the need for centralized 3D archives, including a preliminary needs assessment survey of virtual heritage practitioners. Then we describe several existing 3D cultural heritage repositories, and enumerate a number of technical research challenges that should be addressed to realize an ideal archive. These challenges include digital rights management for the 3D models, clear depiction of uncertainty in 3D reconstructions, version control for 3D models, effective metadata structures, long-term preservation, interoperability, and 3D searching. Other concerns are provision for the application of computational analysis tools, and the organizational structure of a peer-reviewed 3D model archive.

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1. INTRODUCTION

Technological advances in our ability to measure the physical world and in our computer modeling capabilities have led to the creation of an increasing number of high-fidelity 3D models of cultural heritage objects and environments. These models are often supplemented by additional metadata information as well as synthetic reconstructions of missing data. This growing collection of models brings with it new needs and opportunities in the scholarly community and the public it serves: efficient access to, interoperability between, and scientific authentication of the 3D models. In addition, there is a pressing need for archival methods to ensure survivability of these important cultural artifacts.

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We advocate the creation of open repositories of scientifically authenticated 3D cultural heritage models, with standard mechanisms for preservation, peer review, publication, updating, and dissemination of the 3D models. In this article, we consider a number of technical research issues that must be addressed to realize this goal of effective 3D archives.

We first give a brief background of the virtual heritage discipline. Then we characterize the need for centralized 3D archives, including a preliminary needs assessment survey of virtual heritage practitioners. This is followed with a description of several existing state-of-the-art 3D cultural heritage repositories. Finally, we enumerate the primary technical research challenges that must still be addressed to realize an ideal 3D archive, including issues of digital rights management, clear communication of uncertainty and associated metadata, versioning, preservation, and interoperability.

1.1 3D Virtual Cultural Heritage

3D cultural heritage, or “Virtual Heritage,” is the relatively new branch of knowledge that utilizes information technology to capture or represent the data studied by archaeologists and historians of art and architecture. These data include three-dimensional objects such as pottery, furniture, works of art, buildings, and even entire villages, cities, and cultural landscapes. There are three ways that digital tools support this kind of data representation.

- (1) Existing objects can be automatically measured with 3D capture technologies such as laser scanning or photogrammetry.
- (2) Damaged or no-longer extant objects can be modeled by hand with 3D software (e.g., AutoCad, Maya, 3D Studio Max, MultiGen Creator).
- (3) Because file formats of almost all commercially available software can be easily translated, we can combine models made by capture and by hand to create hybrids.

The primary uses of these representations include:

- cataloguing and documentation;
- public outreach and education;
- historical studies; and
- experimental architectural and urban history.

From this list, it can be seen that virtual heritage is a continuation of the traditional activities which scholars and scientists active in the area of cultural heritage studies have been pursuing for several centuries. Whereas the cultural heritage community previously used static 2D forms of documentation (plans, sections, elevations, reconstructions) created on paper and published in print, it is now increasingly using 3D interactive digital tools. This transformation of the medium of expression and publication has meant that virtual heritage has spread rapidly through a large, well-established field, which has generally embraced the new technologies in recognition of their obvious superiority to what they have replaced.

1.2 History of Virtual Heritage

In the 1985 Proceedings of the Annual Conference of Computer and Quantitative Methods in Archaeology (abbreviated as CAA), we find the first major article on 3D capture: Leo Biek’s [1985] article on stereovideo. The first article on 3D hand-modeling was published four years later in the 1989 CAA Proceedings by Arnold et al. [1989], who discussed computer models of the temple precinct at Roman Bath and the Roman military bathhouse at Caerleon, South Wales. In the early 1990’s, J. D. Wilcock’s prediction from the first CAA conference in 1973 [Buckland and Wilcock 1973] that computers would

be used to reconstruct archaeological sites started to be realized. A well-known overview of the virtual heritage scene was given in the 1997 book by M. Forte and A. Siliotti [1997] *Virtual Archaeology*, in which they described several dozen computer reconstructions of sites around the world. For a more recent history of this aspect of the virtual heritage field, see Frischer et al. [2002] and Frischer [2008].

From this 1997 book, we can see that the early computer models served the purpose of illustration, and publications tended to focus on methods and technologies supporting the creation of such illustrations. It is noteworthy that almost all the computer models in Forte and Siliotti's [1997] book were made by private companies, and that none give authorship credit to a professional archaeologist. By the late 1990's, the situation had changed, and with the drop in the costs of creating computer models, many archaeologists started their own 3D projects. Many of these were presented at CAA 1998 in Barcelona [Barcelo et al. 2000], and every annual meeting since then has included an increasing number of papers on this topic. Meanwhile, other professional organizations around the world have started devoting conference time to virtual heritage. These include the "VAST International Symposium on Virtual Reality, Archaeology and Cultural Heritage," "Computer und Archaeologie" (sponsored by the City of Vienna, Austria), "Virtual Retrospect" (presented every other year in Biarritz, France), and "The International Society for Virtual Systems and Multimedia." As another positive sign that virtual heritage has now reached maturity and mainstream recognition, we note the fact that in 2007 the Association for Computing Machinery (ACM) is sponsoring publication of a new journal devoted to the field, the *Journal on Computing and Cultural Heritage*.

There is no reliable count of the number of scholars active in this discipline, nor do we know the number of heritage sites modeled to date. An estimate by a leading practitioner in April 2006 put the number at well over 300 [Sanders 2006]. It is safe to predict that this number will continue to grow geometrically in the next decade as 3D modeling software and data capture systems are mastered and their price falls, even to the point where they are free. See, for example, Google's recently introduced free 3D modeling program, SketchUp, or, for free 3D data capture and processing, MeshLab and the Epoch 3D Webservice [Vergauwen and Gool 2006].

2. NEED FOR CENTRALIZED 3D CULTURAL HERITAGE ARCHIVES

The rapid spread of tools for virtual heritage has inevitably created some new problems. This article outlines a number of research directions to address these problems, and sets forth a major challenge facing the virtual heritage community: the lack of central repositories for the collection, peer review, publication, updating, preservation, and distribution of 3D models of cultural heritage data.

The lack of such repositories has had serious negative consequences, as has been recognized by the community itself (see the following on the preliminary results of a recent needs assessment survey). Foremost among these is the lack of any plan for the preservation of virtual heritage models. Ironically, the very scientists who are doing so much to document and preserve the world's heritage resources are doing little to conserve their own digital products. Secondly, there is no tool to discover whether a particular cultural monument has been digitally captured or modeled; even a Google or Yahoo search is generally fruitless, and there is no Web resource specifically in this area. Thirdly, the creators of virtual heritage products are not rewarded by their peers for creating digital models and related written documentation, because there is no peer review agency evaluating the quality of the work and accepting it for publication. Finally, the end-user, whether a scientist, student, or member of the general public, has no way to access a model, let alone an online resource offering a wide range of high-quality scientific 3D digital models of cultural heritage monuments which he or she may wish to download.

It is our contention that the best way to address these problems is through creation of one or more central services, following the general models of a scholarly press and a photographic archive. The

Table I. Demographics of Respondents (note that provision of this information was optional)

Year of birth	No.	Sex	No.	Country	No.	Position	No.	Models Created	No.
1932-42	1	M	25	Australia	1	Technician	1	1-10	11
1943-52	2	F	6	Canada	4	Cultural ministry	2	11-25	9
1953-62	6			France	4	Indep. scholar	4	26-50	4
1963-72	11			Germany	1	Assist. Prof.	11	51+	5
1973-82	9			Italy	2	Assoc. Prof.	5		
				Mexico	1	Full Prof.	11		
				Romania	2	Other	11		
				S. Korea	2				
				Turkey	1				
				USA	6				

former offers methods of quality control, recruitment of creators, and outreach to the academic community; the latter, methods for economies of scale and sustainability through aggregation and revenue sharing between creators and distributors.

A long-term objective, then, should be the creation of centralized, open repositories of scientifically authenticated virtual environments of cultural heritage sites. By scientifically authenticated, we mean that such archives should accession only 3D models that are clearly identified with authors with appropriate professional qualifications, and whose underlying design documents and metadata are published along with the model. Uncertainties in the 3D data and hypotheses in the reconstructions must be clearly documented and communicated to users. Thus, we envision these 3D archives as realizations of a peer-reviewed journal of 3D cultural heritage models and associated scholarship.

2.1 Needs Assessment Survey Results

Beginning in 2006, we have been running a needs assessment survey conducted online and at professional meetings at which creators of 3D content present their work to their peers. The purpose is to determine whether this “virtual heritage” community feels the need of an online service that would peer review, publish, and provide long-term storage for 3D models of heritage sites. The survey will be administered several more times in 2007 before being closed and the final results published. Thus far, we have received 54 responses from attendees at the annual meetings of “Computer Applications and Quantitative Methods in Archaeology” (held in Fargo, ND, USA from April 18–21, 2006) and “Computer und Archaeologie 2006” (Vienna, Austria, October 18–20, 2006). We have also created an online version of the survey and have invited members of the Humanist Listserv to take it at <http://www.iath.virginia.edu/save/>.

The survey respondents so far come from ten countries. Their median age is 38 years old. The majority are males (80%) and professors at universities (60%). They have already created, on average, between 11 and 25 models of cultural heritage sites, although a surprising number (17%) report that they have made over 50 models. The demographics suggest that the activity of 3D modeling is starting to spread across the planet, with notable (and not surprising) concentrations in North America and Europe. Academics have adapted well to this new way of illustrating the monuments they have long studied.

The results strongly suggest that the virtual heritage community does think that the time for creating such a service has come. Thus far, 90% of all respondents answered “definitely a need” or “probably a need” to the question, “Is there a need for a central repository and distributor of 3D models?” There was also support for offering the following services along with publication: long-term preservation (94% called this “definitely” or “probably” important), peer review (80% called this “definitely” or “probably” important), and interoperability of models with each other (82% called this “definitely” or “probably” important). Brief highlights of the survey results to date are given in Table I and Table II.

Table II. Views About the Need for a Central Repository of 3D Models and Its Features

	Need for central repository?	Long-term preservation?	Peer review?	Interoperability?	File format conversion?
Definitely	23	28	20	15	8
Probably	26	19	20	26	20
No	1	2	7	4	12
No opinion	4	1	3	5	8

3. PRIOR 3D CULTURAL HERITAGE ARCHIVES

A number of 3D archives of cultural heritage models have been created in recent years. While none of them yet realize the full vision of a peer-reviewed, searchable, interoperable repository of scientifically authenticated 3D models, they represent the state of art and the first steps toward this goal. In this section, we review a few such 3D cultural heritage archives.

3.1 Stanford Digital Michelangelo Project

The Digital Michelangelo Project at Stanford University created a 3D archive of Michelangelo's sculpture by digitizing the original marble artworks in Florence, Italy [Levoy et al. 2000]. Ten statues, including the David, were digitized with high-resolution laser scanners, resulting in 3D models with 0.25 mm precision consisting of hundreds of millions of polygons each. The models, as well as the raw range scans and metadata, are distributed via an archive at the Project Web site. However, due to the contract with the Italian authorities, the 3D models and raw data are distributed only to established scholars, who submit an application to the project director for review. An alternative means of access to the models is provided for the general public, via a novel remote rendering system, "ScanView," which is designed to protect the 3D shape of the models from theft while still allowing interactive examination of the models [Koller et al. 2004].

3.2 Stanford Digital Forma Urbis Romae Project

Another very large archive of scanned 3D models at Stanford University is the Digital Forma Urbis Romae Project [Koller et al. 2006]. The Forma Urbis Romae, a giant (18 by 13 meters) marble map of Rome constructed in the early 3rd-century, is an archaeological artifact of primary topographical importance, as it depicts the ancient city at a scale of approximately 1:240. Over one thousand fragments of the map have been recovered; the 3D shape of these surviving fragments were digitized with a laser scanner by the Stanford team, with the intent of developing geometric matching algorithms to search for new joins among the fragments. The 3D models serve as the centerpiece of an online information system about the fragments and the marble map, which also includes digital images, textual analysis, and linked bibliographical data for each fragment, thus providing a complete digital resource for both scholars and the public. Again, access to download the full 3D geometry of the models is limited to approved scholars, although the ScanView protected 3D graphics system is available for anyone to interactively view the fragments.

3.3 UCLA Digital Roman Forum

A real-time virtual reality 3D reconstruction of the Roman Forum as it appeared in late antiquity was developed at UCLA beginning in 1997 [Frischer et al. 2006]. Models of the interiors and exteriors of each building and monument in the Forum were created using 3D modeling software and authenticated by a scientific committee of leading archaeological experts (Figure 1). The real-time 3D database was converted to a digital library format suitable for distribution on the Internet, including QuickTime movies of the 3D models, a time-space map of the Forum, comprehensive metadata about each



Fig. 1. Digital model of the Roman Forum with detailed view of the Rostra, foreground, with Temple of Saturn and Temple of Vespasian, background (left) and a shot of the Forum today from the same vantage point. Photo left is copyright of The Regents of the University of California; photo right is copyright Bernard Frischer.

component of the 3D models, photographs of extant remains, and appropriate articles from Roman topography sources. This presentation of a 3D virtual heritage reconstruction is a pioneering example of an effective scientific committee organization for authentication, as well as an excellent example of detailed metadata describing the uncertainties and design decisions inherent in the hypothetical 3D reconstructions. However, the online archive lacks a means for users to access the actual 3D models and to explore or analyze their geometry.

3.4 CyArk 3D Heritage Archive

The CyArk 3D Heritage Archive is a recent effort to create an online Internet-based repository for cultural heritage site data developed through laser scanning, digital modeling, and other spatial technologies [CyArk]. Currently the CyArk prototype features data from ten prominent archaeological sites, including Angkor, Pompeii, and Ancient Thebes. As the archive was founded by the developers of the Cyra Technologies laser scanner, many of the sites include 3D point cloud survey data, with accompanying images and map data linked together in a spatially-navigable interface with searchable information about each site. The 3D data can be viewed either with a downloadable commercial point-based viewer plugin, or as a QuickTime video.

3.5 Other 3D Archives

A number of other archives of 3D virtual heritage are under construction and being deployed. The Digital Archive Network for Anthropology and World Heritage (DANA-WH) at North Dakota State University is a distributed network of databases of anthropological objects, with custom client software for viewing and measuring the 3D models of fossils and artifacts [Clark et al. 2002]. The Digital Hammurabi Project at Johns Hopkins University aims to perform 3D scanning and archiving of large sets of cuneiform tablets [Digital Hammurabi Project]. Organizations such as the Arts and Humanities Data Service (AHDS) are promoting and maintaining repositories of digital cultural heritage resources, including 3D datasets. Large established digital libraries like the Perseus Project at Tufts University have incorporated some 3D representations into their collections, both in image-based QuickTime formats as well as 3D geometric formats, such as the VRML collection of Greek vases in Perseus [Shiaw et al. 2004]. Commercial archives for 3D models, such as the TurboSquid online clearinghouse for 3D digital artists [TurboSquid], often include cultural heritage models and address many of the issues of searchability and portability to different file formats.

4. RESEARCH CHALLENGES

There persists a number of unresolved research issues concerning the effective management and dissemination of cultural heritage models in a curated 3D archive. Here we enumerate these challenges, in an approximate order of priority, reviewing related prior work and suggesting new directions for research.

4.1 Digital Rights Management for 3D Graphical Models

Three-dimensional models of classical artworks, archaeological artifacts, or historic sites are often very valuable intellectual property, representing treasured cultural heritage and patrimony. The curators of physical artifact collections may be reluctant to allow digitization of their holdings if they would completely lose control of the virtual representations. Likewise, many cultural heritage scholars and content developers would be unwilling to participate in a centralized digital archiving effort that does not offer some guarantees about the security and trustworthy dissemination of their intellectual property. Thus, providing for the digital rights management of 3D models is of paramount importance in the development of 3D cultural heritage archives.

Disseminating interactive 3D content securely is a difficult problem, due to the variety of attacks allowed by the traditional computer graphics pipeline (these possible attacks are discussed in Koller et al. [2004]). Most of the prior research in this area has focused on the a posteriori detection of piracy, not its a priori prevention. While piracy detection and the related problem of verifying model authenticity is important, prevention is the key to successful integration of 3D models into cultural heritage archives. Shortly, we suggest new research directions for protected dissemination of 3D models, both with a posteriori steganographic watermarking methods, and techniques for developing a trusted graphics pipeline to prevent piracy.

4.1.1 Watermarking 3D Models. Steganographic approaches to tracking and authenticating data involve hiding an embedded signature or “watermark” in the digital document to be protected. Specialized watermarking techniques for 3D models can prove highly useful in cultural heritage archives. First, watermarking provides an easy way to verify that a model is authentic, as one can embed the unique signature of a trusted authority in the model itself; users can check that their version is not a digital forgery. Secondly, such a signature could be used to allow only certain similarly signed programmable shaders to be executed by the graphics pipeline, allowing sophisticated use of modern graphics hardware for visualization while preventing an entire class of model recovery attacks. In both of these applications, *fragile watermarks* suffice; these are watermarks that can be easily removed. This is because removal of the watermark will either cause the model to lose its sign of authenticity, or to not be visualized properly.

In other cases, it may be advantageous to distribute 3D models with a hidden *robust watermark* embedded in it; such a watermark is difficult to remove without significantly degrading the quality and usefulness of the model. The presence of a robust watermark on a 3D model would allow the model owner to establish a chain of custody if the model was ever redistributed in violation of the model’s licensing agreement, and pursue enforcement action if desired. For example, 3D models of statues downloaded from a 3D archive could be signed with a unique watermark identifying the initial licensee.

Dozen of research papers in the last decade have described approaches for watermarking 3D graphical models, with varying degrees of robustness to attacks that seek to disable watermarks through alterations to the 3D shape or data representation. Many of the most resilient 3D watermarking schemes are based on spread-spectrum frequency domain transformations, that embed watermarks at multiple scales by introducing controlled perturbations into the coordinates of the 3D model vertices [Praun

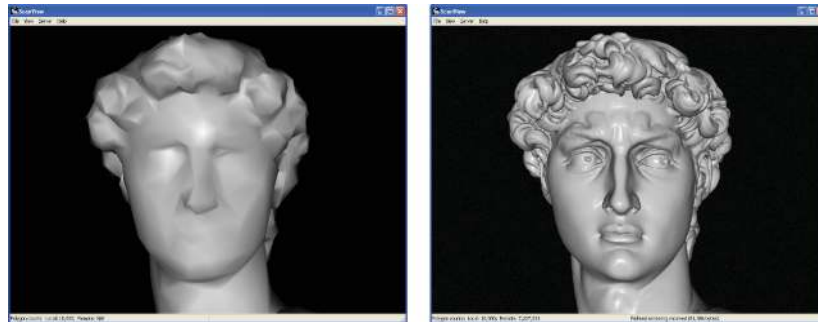


Fig. 2. The ScanView client-side low-resolution 3D rendering (left) is replaced by images from the server-side high-resolution renderings (right) when the user stops moving the mouse.

et al. 1999; Ohbuchi et al. 2002]. Other appearance attributes of the model besides the 3D geometry can be exploited to hide information as well [Zhang et al. 2002].

There is significant room for improvement in both fragile and robust watermarking of 3D models for cultural heritage applications. In particular, the analysis of the impact of watermarking on the quality of the eventual 3D visualization has been at best ad hoc; typically it suffices to say “the models look indistinguishable.” Not only is this approach lacking in rigor, it also gives no insight into the steganographic bandwidth: how much foreign information can be embedded in a model without affecting the quality of the final rendering. Further research could formally study the perceptual impact of watermarking, investigate techniques to guarantee that a watermark will not be perceptible, and design new watermarking schemes that minimally impact the perceived quality of the rendered image for any given amount of information to be embedded. The need to evaluate the perceptibility of the distortions introduced by the watermarking process is especially important for cultural heritage applications, where the human user may care about very subtle features in the model. For example, an art historian studying patterns of chisel marks in the Digital Michelangelo Project 3D models would like to be certain that the subtle variations they are studying represent the chisel mark, and not the watermark!

4.1.2 A Trusted 3D Graphics Pipeline. While steganographic approaches provide a possible means for authenticating 3D models and tracking piracy, the highly valuable and sensitive nature of some cultural heritage 3D models may require methods to prevent piracy a priori rather than merely detect it after the fact. We thus seek new methods for providing a “trusted 3D graphics pipeline” that can protect the 3D data shared via an archive, while still allowing users to interact with and visualize the 3D models.

The state of the art in providing protected interactive 3D graphics of cultural heritage objects was recently advanced by Koller et al. [2004] with the introduction of their “ScanView” remote rendering system. ScanView prevents recovery of a 3D model’s geometry by providing the user with only a very low-resolution version of the 3D model for navigation purposes, and delegating high-quality renderings to a physically inaccessible remote secured server that contains the high-resolution model. These high-resolution images are automatically requested by the client software on “mouse up” events and the rendered images passed back from the server replace the corresponding low-resolution rendering (see Figure 2). Slight distortions are introduced into the images returned by the server to defend against any computer vision reconstruction attacks. Remote rendering provides an immediate level of security because the user does not have any direct access to the 3D model itself, but only rendered 2D images. Additionally, a centralized rendering server as used in the ScanView system has the advantages of consolidating graphics resources, does not require clients to perform computationally-intensive 3D

rendering, and allows the 3D archive maintainer to fully log and monitor usage of the 3D models at a very fine-grained level.

However, such a remote rendering scheme for protected access to 3D models suffers a number of drawbacks. First, a rendering server with sufficient network bandwidth and low latency to all clients may not always be available. The networked nature prohibits offline usage, which may be important to users such as archaeologists working in the field. Additionally, while the ScanView system is effective for viewing and examining static 3D models such as statues or individual artifacts, remote rendering is not appropriate for more continuous, real-time visualization applications such as 3D walkthroughs or immersive virtual reality viewing of large archaeological sites. Thus, we encourage investigation of new methods, such as those outlined next, which may hold better promise for allowing protected sharing of 3D cultural heritage models.

Secure graphics hardware. Digital rights management systems are designed to process their data on potentially hostile hosts; they accomplish this through the use of *trusted players*. A trusted player is a device that can decrypt and manipulate data, but cannot be tampered with. Digital Video Disc (DVD) players operate in this manner; a manufacturer that wishes to sell a DVD player applies for a decryption key that is embedded in the player. This key can then be used to decrypt DVD videos for playback. In a similar way, future 3D graphics cards for personal computers could have a hidden sequence of bits embedded in the hardware that could be used to decrypt 3D models (they would be distributed in the archive in encrypted form) and then render them. This capability would prevent attackers from recovering 3D models by intercepting the graphics API commands, or by capturing the model with a homemade malicious graphics adapter. Some care would need to be taken to ensure that an attacker could not recover the 3D model using either straightforward readback mechanisms or through other systematic misuse of the graphics API. Of course, the well-known fate of DVD encryption provides a cautionary tale for future DRM efforts.

While this hardware systems approach is certainly sound from a security point of view, the architectural implications of adding cryptographic capabilities to graphics hardware have not been studied. Such research is vital to demonstrating the practical viability of this technique for protecting 3D cultural heritage archives, because modern visualization systems rely heavily on the high performance of the graphics pipeline.

A related problem is securing of graphical *shaders*. Modern graphics hardware contains both programmable vertex and fragment engines, and for secure graphics it would be necessary to ensure that a malicious user does not use a vertex program to manipulate or discover the encrypted 3D geometry. Research should investigate the possibility of adding support for *signed shaders* to the graphics pipeline, so that only shaders whose signatures match those of the model could be used. Cultural heritage 3D models may make use of complex shaders to achieve sophisticated rendering effects, so it may also be important for content owners to be able to hide the contents of trusted shaders as well as the 3D geometry.

Ciphermodels and encrypted rendering. One interesting possible approach for allowing protected distribution and usage of sensitive 3D models involves the application *encrypted computation* techniques for digital rights management [Paris and Fiedler 2005]. Whereas more traditional computer security methods address the execution of untrusted software code on a trusted computer, encrypted computation techniques attempt to allow data to be processed on potentially hostile computers. If such a scheme could be implemented, the 3D models would be distributed in an encrypted form, along with a custom viewer that performs the critical rendering functionality directly on the encrypted representation. The 3D model data would never be decrypted, and is thus safe from theft or abuse.

While the encrypted computation problem is widely believed to be unsolvable in general, it is perhaps plausible for the case of encrypted 3D rendering, as the projection of a 3D model onto a 2D screen is done by a very specific, linear function which may be amenable to encrypted computation. The limitations of encrypted computation are currently an open research problem, and encrypted rendering appears far from practical at this time, but warrants further investigation.

Defending against reconstruction attacks. Even if a model can be distributed from an archive and transformed from its 3D description into a 2D image in a secure way, a malicious user can employ a variety of attacks that draw on computer vision algorithms to recover the model from a sequence of high-quality renderings. Koller et al.'s ScanView system employs pseudorandom perturbations to make such an attack ineffective. These random errors need to be introduced into both the viewing parameters and the lighting parameters to defend against both geometric and radiometric attacks. In ScanView, the perturbations are applied when the user releases the mouse button; they rely on change blindness to ensure that the user is not distracted by the introduced randomness. This technique is very effective, but is hard to apply directly to a system that is constantly rendering high-quality imagery. Further research should explore fully the extent to which perturbation defenses can be applied to high-quality interactive rendering, and also design more forward-looking defenses that do not require error to be introduced at all.

Protected geometric analysis. Whereas the techniques described before are concerned primarily with allowing protected rendering and display of 3D models, an ideal secure dissemination system would also allow users a greater degree of geometric analysis of the protected 3D models without further exposing the data to theft. For example, scholarly users of the ScanView system have expressed interest in measuring distances and plotting profiles of 3D objects for analytical purposes, beyond the simple 3D viewing supported in the current system. Database researchers have developed privacy-preserving data mining techniques that extract useful knowledge from databases without significantly compromising data security [Verykios et al. 2004], and we are interested in the applicability of similar methods to the problem of protecting 3D data.

4.2 Metadata for 3D Cultural Heritage Data

While geometric models of cultural heritage sites are the primary information structures to be archived in the 3D repositories that we are addressing, the goal of scientific authentication and scholarly publication requires that such models be supplemented with corresponding textual metadata. We consider three types of metadata that authors will associate with the 3D models deposited in an archive [Frischer 2003].

- (1) *Catalog metadata* include the Dublin Core Metadata Initiative elements such as title, creator, subject, publisher, etc. These are useful for indexing, searching, and citation aids for users, and allow some level of interoperability with other digital library systems that leverage Dublin Core conformity (or other similar standards).
- (2) *Commentary metadata* include information about the evidence for the various elements of the reconstruction and commentary on the modeling design decisions. Alternative views in the scientific literature pertaining to the model are noted, and the reasons for rejecting them are given.
- (3) *Bibliographical metadata* include all the sources, published and unpublished, used in making a model.

The inclusion of these metadata with 3D models are critical to achieve transparency to the user in a way analogous to notes, commentary, and bibliography in a traditional academic print publication. While it is unlikely that perfect reconstruction accuracy relative to an ancient monument's original

appearance can be achieved for complex models, offering complete transparency about the underlying source data and decision making process determines the scientific authenticity of the resulting models.

As part of our research efforts into methods for managing and disseminating 3D cultural heritage models, we should investigate techniques for organizing associated metadata and its effective presentation to users. One particularly interesting concern is methods for allowing interactive exploration of relevant metadata displayed in corresponding locations in the 3D environment. Large urban models of ancient cities, for example, may contain thousands of individual buildings, each of which will potentially have distinct associated metadata. Thus the metadata will need to be spatially referenced to the underlying 3D model, and the 3D exploration interface linked to an appropriate display methodology that combines presentation of 3D and textual metadata elements. The deep inheritance trees that form the basis of many cultural heritage metadata architectures are not likely to be appropriate for organizing 3D metadata, and thus we suggest research into alternative models based on modular networks of shallow metadata objects.

4.3 Uncertainty Visualization for 3D Models

The recent surge in usage of digital visualization tools has created an unfulfilled need for new data visualization techniques which clearly communicate the uncertainty in the underlying data and the depicted phenomena. Leaders in the scientific visualization community have called for researchers to address this representation of uncertainties in an effort to take visualization research to the next level [Johnson and Sanderson 2003]. Current scientific visualization researchers have proposed methods including error bar glyphs, blurring, and false coloring of data to depict uncertainty in their datasets. Researchers in the areas of geography and GIS have described techniques specialized for geospatial data uncertainty visualization, which is typically applied to a 2D domain [MacEachren et al. 2005; Pang 2001]. At the recent NSF-sponsored “Summit on Digital Tools for the Humanities” (Charlottesville, VA, USA, September 28–30, 2005), a group of leading humanities scholars identified “Visualization of Time, Space, and Uncertainty” as one of four primary processes of humanistic scholarship especially ripe for advancement. They called for a suite of software tools and visual conventions to be developed that allow representation and visualization of degrees of uncertainty.

Three-dimensional virtual environments of cultural heritage sites are particularly well suited to motivate and benefit from advances in uncertainty visualization techniques. Many 3D cultural heritage models are reconstructions of sites that are not fully extant nor documented, and thus the reconstructions contain a large number and variety of hypothetical, uncertain elements. The definitive nature of a complete digital 3D model and the nearly photorealistic rendering capabilities of modern computer graphics systems can mask or hide this degree of uncertainty. It is of vital importance, then, that a system for sharing scientifically authenticated cultural heritage models directly facilitates accurate, conspicuous documentation of the uncertainties inherent in the models (the recent London Charter [2006] establishes principles for such transparency in 3D visualization of cultural heritage). Examples of the types of uncertainties in such models include the following.

- Structural Architecture*. For example, did a wall of a church have three or four windows?
- Geometric Dimensions*. Perhaps the wall of the church is known to be between 8 and 12 meters wide, but no further information is known.
- Stylistic Features*. Was the door frame of the church decorated in a Romanesque or Baroque style?
- Temporal Correspondence*. When was the east side of the church expanded to accommodate a new chapel?
- Construction Materials*. Was the west exterior wall stucco or brick?

The 3D model creation process can yield models that may invalidly depict specific answers to these types of questions, even though there is not enough actual knowledge to support such a reconstruction.

To date, there has been insufficient research confronting the problems of uncertainty visualization in 3D virtual environments such as archaeological reconstructions. One research group in Germany in the late 1990's anticipated the problem and proposed using nonphotorealistic (sketch-like) rendering styles for depicting those portions of 3D models with uncertain features [Strothotte et al. 1999]. Other more recent work looked at the specific aspect of visualizing temporal uncertainty [Zuk et al. 2005]. This topic is ripe for experimentation with a variety of approaches for communicating the different types of uncertainties that occur in 3D cultural heritage models; a few possible directions for investigation include the following.

- A New 3D Symbology (a set of 3D glyphs) for Indicating Uncertainty.* Depicting uncertainties in digital 3D reconstructions has been difficult in part due to the lack of any such standardized techniques to borrow from, even in traditional nonelectronic and 2D illustration forms. Thus, we should investigate development of a new set of intuitive 2D and 3D icons that are sufficiently rich to represent the broad range of the types of uncertainty encountered in 3D cultural heritage models.
- Animation Techniques.* Real-time visualization of 3D models allows time-varying depiction techniques to be used for representing uncertainty. As a simple example, an architectural feature on a model that is estimated to be properly located with only a 30% certainty level could be switched on for a corresponding percentage of the time during some fixed interval (its duration chosen so as to minimize user distraction).
- Rendering Techniques.* Modern computer graphics hardware is powerful enough to render complex stylistic effects, even at full interactive rates. A variety of nonphotorealistic techniques, blurring, transparency, false coloring, and other rendering methods could be experimented with to determine effective schemes for representing uncertainty of 3D geometric elements.
- Combining Textual Metadata with 3D Visualization.* Many hypothetical reconstructions are the result of highly complex design decisions that may be difficult or impossible to present iconically in the 3D visualization, and are best described as traditional textual metadata or 2D images. User interaction paradigms for displaying this textual information appropriately should be explored, that depict the metadata in an uncluttered manner, collocated with the 3D visualization.

4.4 Version Control for 3D Models

Version control (also known as revision control or source control) is an established body of techniques for managing multiple revisions of the same unit of information. Version control is most commonly used in the software development process to manage repositories of source code under development. Revision control systems allow software engineers to track and synchronize modifications, and support concurrent work by a large group, as well as development of multiple versions of software derived from a common code base.

The methods of version control as applied to software development can theoretically be adapted to any type of electronic document. There has been some investigation into using version control with CAD systems [Chou and Lim 1986], but no concerted research effort has yet studied the application of version control techniques to the development and dissemination of 3D models. Version control should be a fundamental feature of an effective archive for publishing 3D cultural heritage models.

Virtual environments of cultural heritage sites are a particularly demanding class of 3D models for managing versioning. 3D models of archaeological reconstructions often are changed and evolve over long periods of time as new knowledge comes to light from excavations and further scholarship. Multiple scholars may hold contrasting theories about the appropriate form of the reconstruction, and generate

multiple versions of the same model that are variations on a common basis. Models themselves may depict changes across large temporal spans, with multiple versions corresponding to reconstructions at specific points in time. Additionally, the technological aspects of 3D modeling often require development and distribution of multiple versions of models. For example, 3D models constructed for use in fully interactive, real-time flythroughs are usually of much lower geometric complexity than models used for static, high-quality renderings. Similarly, 3D models may be distributed in a variety of the common 3D file formats, to provide for interoperability and usage by a wide spectrum of users. A version control system for 3D models would efficiently manage the creation, storage, and dissemination of all these potential versions of cultural heritage models.

Future research, then, should investigate the applicability of traditional revision control methods, and further extend them to be suitable for managing large archives of 3D cultural heritage models. We anticipate developing solutions for a 3D model version control system with the following features.

- Tracking of Every Addition, Deletion, and Modification to 3D Models.* As with source code revision systems, each edit should be stored with metadata representing the time of the edit, the identity of the editor, and comments or annotations describing the nature of the modification.
- 3D Difference Computation and Visualization.* Traditional revision control systems for textual documents provide functionality for convenient viewing of the differences between two document versions, similar to the “diff” command available on UNIX systems. We call for investigation of methods for a “3D diff” function that allows rapid 3D visualization of the difference between two versions of a 3D model. This capability could use geometric analysis algorithms and information visualization techniques to automatically identify and then visually highlight the variations among 3D models. Similar techniques for 3D model comparison have been applied before in 3D digital heritage analysis [Niederöst 2001].
- Delta Compression for 3D Models.* For purposes of storage efficiency, revision control systems usually retain only the differences between successive or branched versions of documents; similar techniques for delta compression of 3D geometric components should be investigated.

4.5 Provision for Application of Analytical Tools to 3D Models

Cultural heritage 3D models are most commonly regarded as means for documenting and visualizing of historic sites and artifacts. While these purposes themselves are valuable objectives, we should hope to go beyond visualization and further extend the value of the archived 3D data by facilitating the application of powerful digital analytical tools to the 3D models disseminated via our archives.

Examples of applying analysis tools to 3D cultural heritage models include algorithms for automated reassembly of digitized fragmented objects [Koller and Levoy 2006], or GIS analysis of the spatial distribution of excavated artifacts. Analysis tools for 3D models of reconstructed architectural sites might measure and analyze, for example, the functionality of buildings in terms of room capacity, circulation, illumination, and ventilation. Simulation software for computing illumination and air flow in building interiors already exists, so research efforts should concentrate primarily on developing information architectures and user interfaces such that analytical tools can be efficiently applied in a general way across a wide range of the 3D models to be archived in virtual heritage repositories.

4.6 Indexing and Searching 3D Archives

Other critical functions associated with digital archives of 3D cultural heritage models that requires further research are indexing and searching. As an increasing number of virtual heritage sites are digitized and modeled in 3D, archives will grow to the point where powerful retrieval tools are necessary for users to quickly find the information they seek. An active area of research that is directly relevant is

shape-based retrieval methods, that measure shape similarity between 3D models [Funkhouser et al. 2003; Tangelder and Veltkamp 2004]. We expect that the rich textual annotation required of scientifically authenticated 3D cultural heritage models will often provide appropriate metadata for text matching and effective retrieval, but research results have demonstrated the value of using multiclassifiers for large 3D databases that match on both text and 3D shape simultaneously [Min et al. 2004]. Thus we encourage further research into algorithms for indexing and searching on inherent model attributes that do not depend on human annotation. The ability to search model archives based on 3D shape queries can also be useful in many cultural heritage analysis processes that use 3D models, such as reassembly of fragmented artifacts.

4.7 Interoperability

The creation of 3D cultural heritage archives also requires new solutions for interoperability of 3D models, both with other models in the archive, as well as with external sources. For example, effective archives should support conversion of models to a common format, and provide access to georeferencing metadata that allows different models to be properly located relative to one another in the same coordinate system. Users need to be able to find, retrieve, and combine virtual environment models from different sources. A model of the Roman Forum in 400 A.D. made by one team with MultiGen Creator should ideally interoperate with a model of the neighboring Forum of Julius Caesar made by another team using 3D Studio Max as their modeling software. Models from 3D virtual heritage repositories should also be compatible with centralized common 3D geospatial visualization systems such as Google Earth, which are quickly gaining popularity as platforms for presenting geolocated information.

These needs are, of course, by no means limited to 3D model archives. They loom large throughout digital culture, as has been recognized by the European Union in an influential study by Mulrenin and Szauer [2002, page 186]:

From a technological point of view, providing seamless, integrated access to services and cultural heritage resources is primarily a question of convergence and interoperability. At the basic level, convergence and interoperability mean providing users with the capacity to treat multiple digital collections in various cultural institutions as one. For cultural heritage institutions, one of the primary obstacles to providing integrated seamless access over computer networks relates to the fact that over the Internet, protected databases or online catalog[s] cannot be directly searched.

4.8 Long-Term Preservation of 3D Data

One of the most pressing needs for 3D cultural heritage archives is ensuring the survivability of the models [Frischer et al. 2002]. More and more 3D models are being created by digital archaeologists and architectural historians around the world, but no one is collecting them, let alone addressing ways of preserving them. In a sense, the activity of 3D modeling can be viewed as an integral part of conservation science, and, indeed, in a recently proposed ICOMOS charter on archaeological site presentation, three articles explicitly discuss the appropriate uses of computer models as substitutes for restoration and anastylosis [Frischer and Stinson 2003]. Anecdotal evidence suggests that even digital models that are only two or three years old are losing their original functionality and information richness because of poor archival practice. CAD software products used to create virtual heritage models belong to a rapidly changing market segment, which means that updated versions are inevitable (on the order of every 18 months) and full reuse of data (without loss of information) is not secured at all.

Once again, the problem transcends 3D models. As Mulrenin and Szauer note [2002, page. 210]:

Not brittle papyrus and crumbling mortar is the most severe threat to our cultural heritage today, but, as Mary Feeny expressed it, “the death of the digit” [Feeny 1999]. This ‘death of the digit’ is related primarily to two factors that put at jeopardy current efforts in archiving and preserving our digital cultural heritage: first, technology develops ever more rapidly, reducing the time before a particular technology becomes obsolete; and secondly, unlike their analogue counterparts, digital resources are much more ‘unstable’ with the effect that the integrity and authenticity of digital cultural resources is corrupted.

Hence Mulrenin and Szauer [2002] recommend to the European Union that “the worst thing to do is adopting a ‘sit and wait’ attitude. Instead, cultural heritage institutions should actively approach the preservation issue and try to take as much control as possible. This means to actively manage the life cycle of digital resources, from data creation and data management to data use and rights management.” We agree with the general policy propounded by Mulrenin and Szauer [2002] and propose the application of it to the specific case of proactive approaches to the collection, categorization, dissemination, and preservation of 3D models of cultural heritage sites.

The digital libraries community has made strong progress in technical solutions for preservation and reliability of access, and we recommend extending and applying these techniques to 3D archives. The LOCKSS system [Rosenthal and Reich 2000], for example, has proven highly effective for preservation of Web-published academic journals, and it would be fruitful to consider the ramifications of a similar peer-to-peer, highly replicated architecture for 3D archiving, along with appropriate implementations of transparent format migration or emulation schemes.

4.9 Organizational and Logistical Structure of a Peer-Reviewed 3D Archive

The existing model of traditional peer-reviewed print journals provides the inspiration for scientifically authenticated online 3D cultural heritage archives. Further research is necessary, however, to study and develop the most appropriate organizational, logistical, and sociological structures for curation of this new type of venue for dissemination of research results. As a first step, we anticipate that the traditional structure with an appointed editorial board is suitable, with editors forming committees of specialized reviewers to peer review submissions of 3D models to the archive. The editorial board would consist of expert scholars in the relevant subject domains (e.g., classical architecture, art history, 3D digitization). A standardized report form would be designed for the archive, that would be published with each 3D model. Other logistical issues to be explored would include licensing and copyright arrangements for 3D models, and schemes by which the 3D model developers could receive revenue from users who access models from the archive, when desired.

5. CONCLUSION

Successfully addressing these research challenges will dramatically improve the state of the art in the management and utility of 3D cultural heritage model archives. Scholarship in nearly all fields of the humanities and sciences will be empowered by having reliable, sustained access to authenticated 3D models. The realization of a peer-reviewed resource for publishing 3D models and clearly recognizing their validity will further encourage the rapid growth and acceptance of virtual heritage as a compelling new manner of communicating knowledge.

Resolving these issues will involve an unusually broad multidisciplinary research effort. The technical computer science aspects themselves span the fields of computer security, computer graphics, databases,

computational geometry, visualization, and information retrieval, to name only a fraction. Domain expert humanist scholars will be necessary to define the scientific and technological user needs of the virtual heritage community, such as specifying metadata architectures appropriate for their objects of study.

At the University of Virginia, our long-term objective is to create a 3D cultural heritage archive that fulfills the vision outlined here. Our multi-year SAVE initiative (“Serving and Archiving Virtual Environments”) has been supported by the National Science Foundation to tackle the associated research problems, with an initial focus on development of digital rights management methods for protecting and sharing 3D models, as well as conducting a needs assessment of potential contributors to an open 3D archive. Currently we are studying the problems of uncertainty visualization and 3D versioning, and we anticipate the implementation and deployment of a pilot version of a peer-reviewed SAVE 3D cultural heritage archive that will give us a testbed to begin addressing the more systems-oriented and organizational research challenges. We look forward to tackling these problems, along with other researchers in the computing and cultural heritage community!

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