

Visualizing Temporal Uncertainty in 3D Virtual Reconstructions

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Abstract

Uncertainty in various forms is prevalent throughout Archaeology. With archaeological site data in particular, the dating regularly has significant uncertainty. In this paper we present an application that enables integrating and visualizing the temporal uncertainty for multiple 3D archaeological data sets with different dating. We introduce a temporal time window for dealing with the uncertainty and review various visual cues appropriate for revealing the uncertainty within the time window. The interactive animation of the time window allows a unique exploration of the temporal uncertainty.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - Virtual Reality; J.2 [Physical Sciences and Engineering]: Archaeology; I.3.6 [Computer Graphics]: Methodology and Techniques - Interaction Techniques

1. Introduction

Uncertainty in various forms is prevalent throughout Archaeology. Archaeological site data can be recorded in numerous formats ranging from hand drawn sketches to ground penetrating radar. All of the recorded data usually represents a minuscule fraction of the information regarding the visual appearance of a site over time and so missing data forms a major component of the uncertainty. Of the data that are available the dating regularly has significant uncertainty.

All archaeological data have a relative chronology value (for example, an artifact's placement within a stratigraphic sequence, or the addition of a wall to an existing building), and some data also have an absolute chronology value (for example, coins bearing mint dates, inscriptions mentioning an event during the reign of a certain ruler) that archaeologists can discern. In both conditions, dating must be thought of as representing either a span of time during which an event occurred, or a point in time before or after which an event occurred. Furthermore, many archaeological sites and their data sets are incomplete or disturbed, rendering their chronological value obscure. All chronology pertaining to archaeological data thus contains uncertainty.

This uncertainty should be integrated into any visualiza-

tion to improve the cognitive task of spatio-temporal understanding. To aid in comprehension we present a time window for the animated visualization of the temporal uncertainty. We also analyze the applicability of various visual representations appropriate for revealing temporal uncertainty in interactive 3D scene reconstructions.

1.1. Visualization

Often archaeological data is visualized at a specific time in the past. This can be categorized as a reconstruction, which when using computer graphics is often called a virtual reconstruction. This has been performed on ancient sites such as the Visir Tomb [PBM93] up to the recent past with the Dresden Frauenkirche [Col93]. This methodology can even be extended into the future for illustrating models of restoration or deterioration.

Usually within an archaeological site, however, data are collected representing various periods of time. Site data is 3D spatial data acquired during an excavation but the dating of each of the artifacts is not as precise as the spatial location. The 3D position of an object represents either the final position of an artifact and thus its last probable use prior to burial, or it represents its original, intended use and is thus

in situ, in its original placement on a site. A decision must be made as to which location the viewer desires to visualize. Integrating the *in situ* object placement within a virtual reconstruction (of approximate object burial date) can help the archaeologist to visualize the use of an object, or hypothesize why the object came to rest in that position. Two published examples of the visualization of last use locations relative to *in situ* architectural reconstructions, are the location of bifaces, scrapers, and debitage (tools and fragments) within a prehistoric pithouse [PFH95], and lamps and coins inside the Great Temple of Petra [AVLJ01].

Reconstructions and their integration with archaeological site data may allow more accurate hypotheses to be made. Virtual reality can allow the archaeologist to understand the past context of the 3D spatial layout of their data [vFL*00]. When using a 3D model various lighting or sky/star models can be applied to test other theories as well. For example, would a certain location within a building have adequate natural lighting for the inhabitant to perform a specific task? All of these techniques can provide valuable new tools to aid in interpreting the data.

Using the computational power of current consumer-level computer graphics technology, interactive animation of complex 3D scenes is now possible. The animation of time provides a powerful visualization which allows complex 3D spatio-temporal changes to be compared in a natural way. Currently most archaeological visualizations represent spatially static scenes of a speculative nature that represent specific time periods. The following discussion will outline how to extend this type of visualization by adding increased comprehension of the temporal changes and uncertainty using interactive animation.

2. Time Windows and Interactive Animation

Any artifact or structure may have an estimated timeline based on a creation and destruction date (the destruction may be in the future). Using these dates the 3D scene for a specific date, or an animation frame, can be constructed by simply finding which data sets have a timeline that overlaps the viewing date. However the overlap will be influenced by the uncertainty in the creation and destruction dates. Uncertainty in these dates may be statistical such as from dating technology, or more abstract such as when based on scientific judgement [RB00]. This judgement may consider things such as the likelihood of contamination or just be an expert estimate based on seriation (relative chronology based on associations).

2.1. Time Windows

The computer generation of an animation frame may use the photorealistic rendering analogy of the shutter speed of the camera taking the picture. This allows effects such as motion blur to be recreated for moving objects, or a moving

camera, by sampling the view repeatedly (while the shutter is open) and then blending the pixels together. In our context we suggest that the frame (viewing time) also take into account temporal uncertainty.

In expanding the camera shutter concept to a much larger timescale we create a time window. This allows events on either side of a specific date to be viewed to take into account uncertainty in the actual viewing time. It can provide a visualization to help in answering a question like: what would a person have seen if they visited the site between 200 and 210 BCE? Arbitrarily expanding the time window also enables the viewer to see how later and earlier construction relates in an intuitive way. The time window could also be interpreted reciprocally giving all artifacts temporal uncertainty equal to half the time window.

The time window is illustrated in Figure 1. The time window's width (range of time) can be controlled by the user. This window of time allows data that comes within range of the viewing date to be visualized in some way. The time window allows two different types of uncertainty to come into play: the uncertainty in the original dating, and the uncertainty over the time window.

Either the time window or timeline uncertainties can be mapped to probability density functions or other schemes. As an example, for the time window the centre can be thought of as absolute certainty (equal to a probability of one) and then certainty (probability) can drop off based on a function (e.g. Gaussian) to zero at each end of the time window. For the time window alone the uncertainty for an object would be the maximum certainty function value that the object timeline overlaps. These certainty functions over the time window and timelines can be used independently or combined. The uncertainty measures can then be used to create visual representations that depict various levels of uncertainty other than the obvious inclusion or exclusion from the scene.

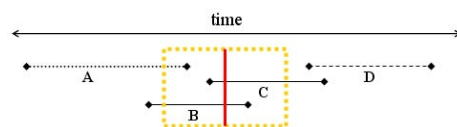


Figure 1: Time Window. Segments A, B, C, and D represent data sets and their timelines. The line down the centre of the box represents a specific viewing time, and all data sets that overlap this time are displayed normally (B & C). The dotted-line box extends the standard viewing time to form a time window. The data sets that only overlap the time window and not the viewing time may be rendered in a way to indicate uncertainty (A). All data sets outside the time window would not be displayed (D).

2.2. Interactive Animation

Archaeological animations often are restricted to a specific reconstruction date and provide a fly-through or a virtual reality experience [FS97]. In some cases a partially interactive animation over time is created [VPW*04], but these do not include uncertainty. In these scenarios the rendered frame represents a small window in time (usually infinitely small) in contrast to our time window concept.

As time is experienced in a continuous and unstoppable manner, it is natural to want to explore time interactively. We provide a graphical user interface in the form of a slider to allow the user to directly control the temporal position of the time window. By manipulation of the time slider and time window the user can create an interactive temporal animation either forward or backward in time. The user controllable animation along with uncertainty visualizations may provide better temporal comprehension.

3. Visual Representations

Given an uncertainty metric there are numerous ways to render a 3D artifact within a scene to express the uncertainty. We are concerning ourselves only with uncertainty in time while ignoring the uncertainty in the other dimensions. Obviously the uncertainty in spatial position is relevant, and is temporally dependent, as with the Arrigo VII funerary complex reconstruction [BBC*04], but it is beyond the scope of this paper. We are also limiting our discussion to visual integrations into a standard 3D virtual reality scene that can be intuitively understood. Honouring these restrictions creates a visual 3D scene rendering that is compatible with normal virtual reality systems and only slightly reduces the options.

Non-photorealistic rendering (NPR) methods have been shown to be able to depict uncertainty required to express speculative designs or constructions [SPR*94, SS02]. Strothotte *et al.* [SPM*99, SMI99] reviewed aspects of non-photorealistic rendering and how they can be used in representing uncertainty in virtual reconstructions. They show how sketch-like renditions and the use of variable transparency can express the speculative nature of archaeological reconstruction. The authors found that photorealistic detail distracted from the fundamental questions of the domain experts. They conclude that more methods of visualization and interaction are required for expressing the appropriate level of uncertainty. Practical aspects of an implementation using these techniques were presented by Freudenbert *et al.* [FMRS01]. Roussou and Drettakis [RD03] have discussed photorealistic rendering, NPR, and interactivity, and found they all have an important role in the perceived realism.

Reusing the camera shutter analogy and sampling the scene over the time window (and including data timeline uncertainty) is the most straight forward visualization. While it would be appropriate to integrate the certainty over the time window, we simply used the maximum certainty in the time

window. If the maximum certainty of an artifact was 0.2 as a probability then the opacity could be set to 0.2 to provide the same effect as motion blur if the object was removed after $2/10^{th}$ of a frame. Where spatially incompatible artifacts occupy the same space they will intersect each other.

3.1. Visual Cues

A visual cue can be defined as any visual encoding (color, size, animation, etc.) and used to communicate meta-data. Arbitrary visual cues beyond the motion-blur (transparency) from the standard camera shutter model move us into styles of non-photorealistic rendering. In the current context a visual cue is any visual encoding used to distinguish levels of uncertainty. Some visual cues may be applied to a single artifact while others may cover the entire scene. For example if fog is applied to only a single object it will be perceived as color blending, similar to a color saturation cue rather than environmental fog. Visual cues may also be overloaded in that they have implicit meanings beyond their use as a representation of uncertainty. This is true for cues such as fog and blur/depth-of-field [Mac92, KMH01], as a virtual reality rendering may already use these as depth cues [War04] (visual encoding of the distance to objects in a scene).

In Pang *et al.*'s survey [PWL97] of uncertainty visualization there are numerous applicable methods including: side-by-side views, pseudo-color, contour lines, blinking, material properties, texture mapping, bump mapping, oscillation, displacement, and blur. They categorize methods for visualizing uncertainty into the groups: add glyph, add geometry, modify geometry, modify attributes, animation, sonification, and psychovisual. We introduce a cue into Pang *et al.*'s animation category with the use of a rising/sinking animation during continuous time changes (a form of displacement). The rising/sinking animation provides a natural transition animation similar to that of time-lapse photography of construction. A drawback of the rising/sinking cue is that it may be misinterpreted in a static scene.

The two visual cues of transparency and the rising/sinking animation are used to illustrate the time window technique for presenting the uncertainty. Figure 2 contains photographs with specific dates assigned matching the photograph's contents. The photographs represent a series of sites which exist at the current time. They are the Giza Pyramids, the Ram-museum, and the Kiosk of Qertassi near the Temple of Kal-absha. The figure shows three snapshots of the window containing the 3D scene view and time slider view. The uncertainty based on the relative position of a timeline in the time window is visible in the top two images. The timeline of each data set (photograph) is shown in a different color and from top to bottom and corresponds to the photos from left to right. Visual cues may be classified on various attributes from perceptual to practical. Bertin's framework called the Properties of the Graphic System [BbWJB83] classified visual variables (which often may be used as cues) on the ba-

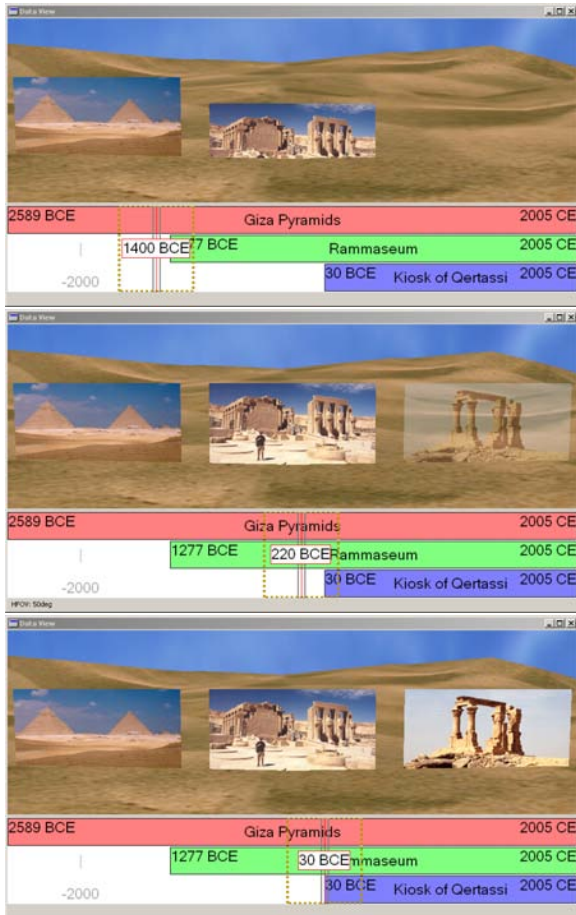


Figure 2: *Uncertainty cue animation.* Viewing dates (frames) from top to bottom of 1400, 220, and 30 BCE respectively. Time window constant at 300 years. Top image shows rising/sinking cue, middle image transparency, and bottom image no uncertainty.

sis of their characteristics such as the potential for immediate perceptual group selection, natural perceptual ordering (not learned), ability for quantitative comparisons, and length (the number of discernible elements that can be represented in the set, i.e. cardinality). A summary of some visual cues appropriate for 3D rendering and relevant characteristics (including Bertin's length and order) are presented in Table 1. The table also indicates whether direct programming of the graphics processing unit (GPU) would be advantageous, and this will be discussed in more detail in Section 5.2. The practical length of a visual cue depends on the visual size of the rendered artifact in the frame and so the categories of small, medium, and large, are relative generalizations.

4. Implementation

Our application, ArkVis, was developed for visualizing 3D archaeological data along with their temporal uncertainty. ArkVis allows the user to import multiple 3D data sets and assign various properties to them. The most important of these properties are the dating, or creation and destruction dates, of the physical artifacts or structures composing a data set. Uncertainty may be assigned to each of these dates.

The data may be interactively viewed in a 3D perspective scene. The user selects a date using the time slider and a scene is automatically generated representing the scene (archaeological or site) at the given time. The user may also drag the time slider to create a temporal animation. Once a scene is constructed for a specific time window, ArkVis allows the user to navigate (walking or flying) through the site at that specific time in history. They may also interactively manipulate the time window to provide a larger or smaller portal into the near future and near past. Various visual cues for the temporal uncertainty of the data may be selected interactively.

The time window may be shifted along with the time slider or may be specified by directly drawing it. As the concept of vagueness is often tied to uncertainty we also provide the approximate input of values by allowing the time window to be "sketched" out. This process is shown in Figure 3.

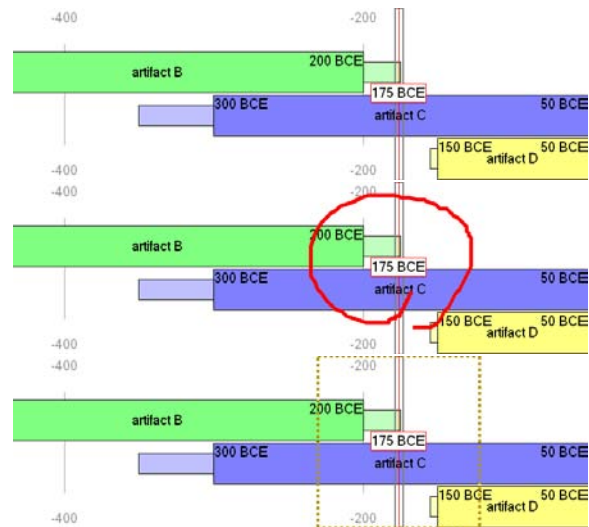


Figure 3: *Approximate time window specification.* Top image: no time window only artifact C visible. Middle image: approximate time window specified with mouse input. Bottom image: new time window based on roughly guided input in which artifacts B and D would be visible but could be rendered with visual cue of uncertainty. Timeline boundaries with uncertainty are indicated by smaller sized extensions with lower color saturation.

Table 1: Visual Cue Characteristics

visual cue	length	order	artifact/scene	GPU
transparency	small	Y	artifact	Y
color change	medium	N	artifact	Y
wireframe	2	Y	artifact	N
line style (NPR)	large	N	artifact	Y
shading/hatching (NPR)	large	Y	artifact	Y
floorplan only	2	N	artifact	N
rising/sinking	large	Y	artifact	N
animated warping of surfaces	medium	N	artifact	Y
blur	small	Y	artifact	Y
fog/haze	small	Y	scene	N
rain/snow	medium	Y	scene	Y

ArkVis was written in C++ using Microsoft’s Visual Studio. Trolltech’s window and widget library Qt was used. The 3D scene and visual cues are rendered using OpenGL and Nvidia’s Cg language for GPU programming. Model loading was based on the Lischke’s 3DS import library [Lis05], and the sky rendering was based on Sempé’s sky demo [Sem05].

5. Results

Archaeological data recorded for the Maḥram Bilqīs sanctuary complex in Mārib, Republic of Yemen [Gla98, Gla99, Gla02] has been used to illustrate the system. The most recent spatial data is of the main oval wall of the temple, provided by a recent survey taking accurate measurements. This data represents a structure deteriorated by looting and time. The earlier data is a theoretical reconstruction of the site at an early date. These two data sets are compared using different visual cues in Figure 4. Interactive animation provided by the time slider and time window allow smooth transitions between the two data sets. This along with the uncertainty visualization may allow the user to more easily understand the assumptions in the earlier theoretical data set.

5.1. Uncertainty Tasks

While simply visually revealing the uncertainty (at the Boolean level) can clearly be achieved it is not clear what representations are most appropriate for specific tasks. While some of the cues have a length above a Boolean indicator they may not be appropriate or may lead to confusion. For the task of simply eliciting possibilities most of the cues in Table 1 would work.

Amar and Stasko’s general *Rationale-based Task* category of *expose uncertainty* requires both the presentation of the uncertainty and showing the possible effect of the uncertainty on outcomes [AS04]. Uncertainty cues such as transparency and wireframe directly allow the possible effects on outcomes to be seen, as the user can ignore the data and consider that it did not exist at that time. Once uncertainty is

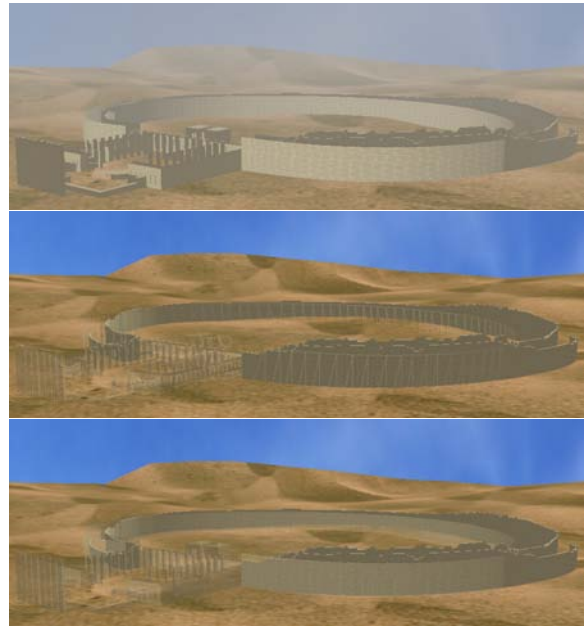


Figure 4: Juxtaposition of theoretical reconstructions and survey data. Top image: incompatible data with scene haze (no data set uncertainty cues). Middle image: wireframe and transparency uncertainty cue. Bottom image: transparency uncertainty cue.

revealed simply providing interactive toggling of a data set also affords this.

Kirschenbaum and Arruda found that for some spatial problems a graphical representation of uncertainty may improve the judgements of decision makers [KA94]. We hypothesize that this would also apply to spatial decisions that must account for temporal uncertainty. Future work could determine the cognitive tasks and set of applicable visual cues that could be used to test this hypothesis. For example, assuming Cohen *et al.*’s cycle of metarecognition [CFW96]

was applicable, then the time window could provide visual queries to aid in the testing of incomplete, conflicting, and unreliable information.

5.2. Interactive Rendering Considerations

When the time slider is used to create an animation, on each sequential frame the time window moves and so the temporal uncertainty may change for all data sets. The data for a virtual reconstruction may be very large even before adding multiple temporal versions. Therefore any procedural rendering method can reduce resource requirements by simply modifying the single representation of each data set during the rendering process. As interactive animation is required using the graphics processing unit to its full potential is desirable.

The uncertainty visualization method categories of modify geometry, modify attributes, and animation [PWL97] are highly suited for interactive graphics. Using graphics processing unit (GPU) programs to perform procedural rendering, one can work with a single representation of the scene and directly modify the visual appearance based on the uncertainty metric (e.g. transparency can be changed without modifying the model attributes). The uncertainty value assigned to each data set can also be used to determine when a different GPU program is used (e.g. to provide a sketch-like quality).

5.3. Visual Cue Discussion

We have simulated an ancient Egyptian archaeological site to more clearly demonstrate some visual cues for temporal uncertainty. The site is shown with its associated data timelines in Figure 5. This site contains different dating for the columns, sphinxes, and the main statue. Various visual cues are illustrated for the specific viewing date of 1575 BCE and a time window of 100 years (both the statue and sphinxes are uncertain with this temporal configuration) in Figures 6 and 7.

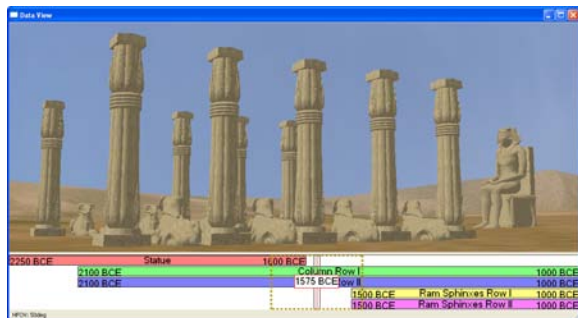


Figure 5: Simulated archaeological reconstruction. Rendered with scene haze. No data set uncertainty visualization.

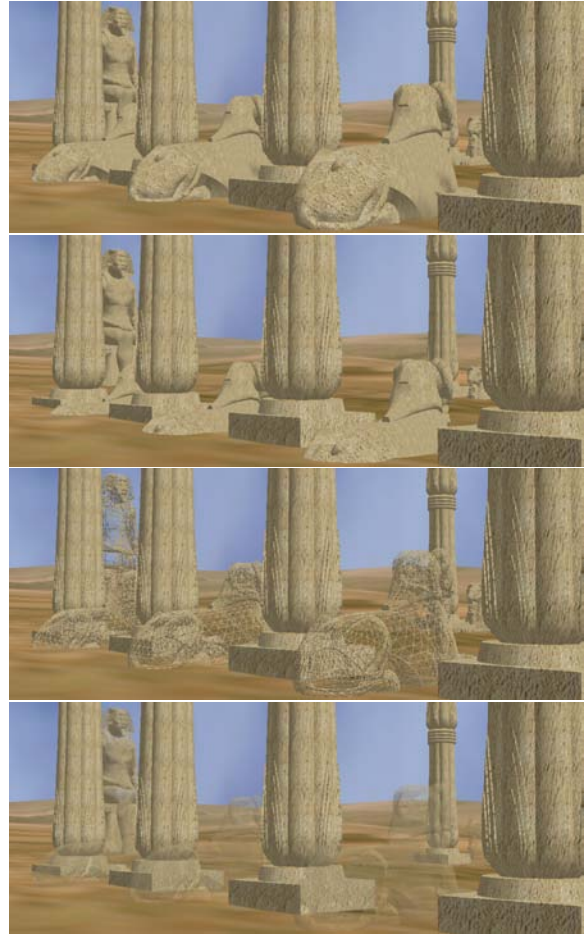


Figure 6: Uncertainty cues. From top to bottom: no cues, rising/sinking cue, wireframe, and transparency.

Cues implemented using standard OpenGL are usually efficient but have limitations. To achieve correct transparency effects with OpenGL (or any Z-Buffer depth sorting) one must ensure that transparent data sets are rendered last and in back to front order. While this can easily be done at the object (artifact) level it is not usually interactively feasible at the polygon/pixel level. Therefore basic OpenGL transparency is not guaranteed to provide accurate results with complicated objects and scenes. The wireframe cue also has its drawbacks as it may be misleading. Wireframe rendering reveals much of the underlying polygonalization and so is dependent on manner in which the object was created. It may be better to determine the silhouette and crease edges of the objects in the data sets and only display those as lines. To do this we could utilize techniques similar to those of technical illustration presented by Gooch *et al.* [GSG*99]. It may also be possible for the modeller to design objects so

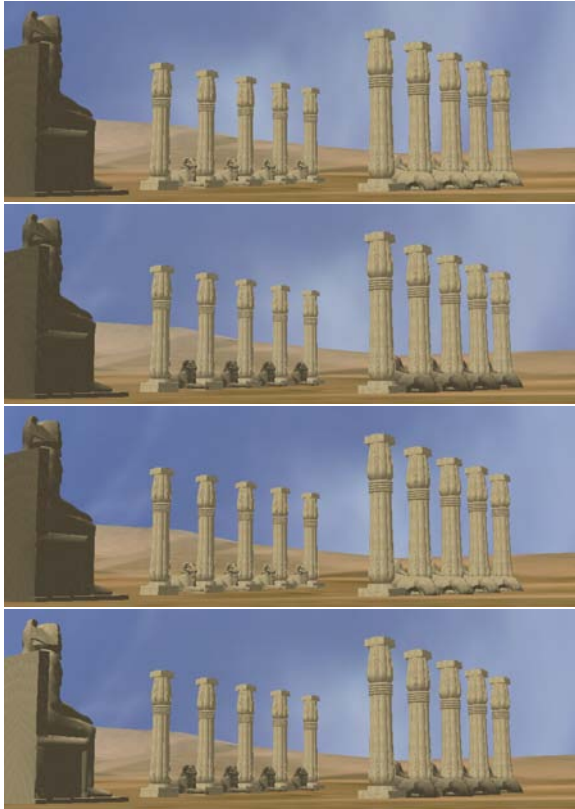


Figure 7: *Animated shading uncertainty cue (GPU program). Uncertainty controls the presence and frequency of shadows. Higher uncertainty has higher frequency and so the sphinxes are in and out of shadow more often than the statue.*

that they provide a suitable look when rendered in wireframe mode.

Each visual cue will have its own benefits and drawbacks. Visual cues that can be created using GPU programs benefit from increased flexibility (they are not bound by the fixed OpenGL rendering pipeline) and potentially faster performance. Those that are more intuitive will be more accessible to the general public (e.g. transparency, fog). More complex cues may require learning, but then may allow domain experts to encode multiple types of uncertainty. Determination of which cues are the most appropriate to use will depend on task and hardware considerations.

6. Conclusions

We have described a method and an application, ArkVis, that provides an easier way to cognitively merge multiple data sets that represent different periods in time. In ArkVis after importing and entering minimal information a scene can be navigated arbitrarily in time and space. By controlling the

time window, data from non-overlapping periods in history can be spatially integrated with user selectable visual cues revealing the uncertainty. The animated time window is intended to provide a new look at the progression of time at an archaeological or cultural heritage site.

Visualizations of archaeological and cultural heritage sites serve two distinct user groups: the general public, and domain experts. They can be useful to the general public in providing comprehensible visual explanations and to domain experts by allowing them to see their data. While NPR renderings may better serve the cognitive tasks such as hypothesis building [SMI99], some tasks may benefit from other types of rendering that may illustrate another person's conceptualization [RD03]. For example, at a museum a photorealistic rendering style may best help people conceptualize that an ancient site was a living community. Interactive animation that can allow the user to select the type of rendering style provides the most flexibility.

Similar to problems observed with photo-realistic drawings used in preliminary drafts of architecture [SPR*94], the clean data sets provided for theoretical reconstructions often give the false impression of accuracy and completeness. They may give a viewer the impression that this is exactly how it did look, even though a large portion may be artistic interpretation. Therefore we feel it is important to give the same regard to temporal uncertainty as spatial uncertainty. We hope that the visual differences revealed by controlled blending and contrasting of data from different times, as well as different sources, can provide new insights, thereby providing an improved understanding of the past.

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References

- [AS04] AMAR R., STASKO J.: A knowledge task-based framework for design and evaluation of information visualizations. In *Proc. of the IEEE Symposium on Information Visualization* (2004), pp. 143–149.
- [AVLJ01] ACEVEDO D., VOTE E., LAIDLAW D. H., JOUKOWSKY M. S.: Archaeological data visualization in VR: analysis of lamp finds at the Great Temple of Petra, a case study. In *Proceedings of the Conference on Visualization 2001 (VIS-01)* (Piscataway, NJ, Oct. 21–26 2001), Ertl T., Joy K., Varshney A., (Eds.), IEEE Computer Society, pp. 493–496.

- [BBC*04] BARACCHINI C., BROGI A., CALLIERI M., CAPITANI L., CIGNONI P., FASANO A., MONTANI C., NENCI C., NOVELLO R. P., PINGI P., PONCHIO F., SCOPIGNO R.: Digital reconstruction of the Arrigo VII funerary complex. In *VAST 2004: Virtual Reality, Archaeology and Cultural Heritage* (2004).
- [BbWJB83] BERTIN J., BY WILLIAM J. BERG T.: *Semiology of Graphics*. The University of Wisconsin Press, WI, 1983.
- [CFW96] COHEN M. S., FREEMAN J. T., WOLF S.: Metarecognition in time-stressed decision making: Recognizing, critiquing, and correcting. *Human Factors* 38, 2 (1996), 206–219.
- [Col93] COLLINS B.: From Ruins to Reality - The Dresden Frauenkirche. *IEEE Computer Graphics and Applications* (Nov. 1993), 13–15.
- [FMRS01] FREUDENBERG B., MASUCH M., RÖBER N., STROTHOTTE T.: The Computer-Visualistik-Raum: veritable and inexpensive presentation of a virtual reconstruction. In *VAST '01: Virtual Reality, Archeology, and Cultural Heritage* (2001), ACM Press, pp. 97–102.
- [FS97] FORTE M., SILIOTTI A. (Eds.): *Virtual Archaeology: Re-Creating Ancient Worlds*. Harry N. Abrams, 1997.
- [Gla98] GLANZMAN W. D.: Digging deeper: the results of the first season of activities of the AFSM on the Maḥram Bilqīs, Mārib. In *Proceedings of the Seminar for Arabian Studies* (1998), vol. 28, pp. 89–104.
- [Gla99] GLANZMAN W. D.: Clarifying the record: the Bayt Awwām revisited. In *Proceedings of the Seminar for Arabian Studies* (1999), vol. 29, pp. 73–88.
- [Gla02] GLANZMAN W. D.: Some notions of sacred space at the Maḥram Bilqīs in Mārib. In *Proceedings of the Seminar for Arabian Studies* (2002), vol. 32, pp. 187–201.
- [GSG*99] GOOCH B., SLOAN P.-P. J., GOOCH A., SHIRLEY P., RIESENFELD R.: Interactive technical illustration. In *Proceedings of the Conference on the 1999 Symposium on interactive 3D Graphics* (New York, 1999), Spencer S. N., (Ed.), ACM Press, pp. 31–38.
- [KA94] KIRSCHENBAUM S. S., ARRUDA J. E.: Effects of graphic and verbal probability information on command decision making. *Human Factors* 36, 3 (1994), 406–418.
- [KMH01] KOSARA R., MIKSCH S., HAUSER H.: Semantic depth of field. In *IEEE Symposium on Information Visualization 2001 (InfoVis 2001)* (San Diego, CA, USA, 22–23 2001).
- [Lis05] LISCHKE M.: 3DS import library, <http://www.lischke-online.de/3DS.php>, 2005.
- [Mac92] MACEACHREN A. M.: Visualizing uncertain information. *Cartographic Perspective* 13 (1992), 10–19.
- [PBM93] PALAMIDESE P., BETRO M., MUCCIOLI G.: The virtual restoration of the Visir tomb. In *Proceedings of the Visualization '93 Conference* (San Jose, CA, Oct. 1993), Nielson G. M., Bergeron D., (Eds.), IEEE Computer Society Press, pp. 420–423.
- [PFH95] PETERSON P., FRACCHIA F. D., HAYDEN B.: Integrating spatial data display with virtual reconstruction. *IEEE Computer Graphics and Applications* 15, 4 (July 1995), 40–46.
- [PWL97] PANG A. T., WITTENBRINK C. M., LODHA S. K.: Approaches to uncertainty visualization. *The Visual Computer* 13, 8 (1997), 370–390. ISSN 0178-2789.
- [RB00] RENFREW C., BAHN P.: *Archaeology: Theories Methods and Practice*, 2nd ed. Thames & Hudson, 2000.
- [RD03] ROUSSOU M., DRETTAKIS G.: Photorealism and non-photorealism in virtual heritage representation. In *VAST 2003: Virtual Reality, Archaeology and Cultural Heritage* (2003), pp. 51–60.
- [Sem05] SEMPÉ L. R.: OpenGL SkyDomes, <http://www.spheregames.com/articles.asp>, 2005.
- [SMI99] STROTHOTTE T., MASUCH M., ISENBERG T.: Visualizing Knowledge about Virtual Reconstructions of Ancient Architecture. In *Proceedings Computer Graphics International* (1999), The Computer Graphics Society, IEEE Computer Society, pp. 36–43.
- [SPM*99] STROTHOTTE T., PUHLE M., MASUCH M., FREUDENBERG B., KREIKER S., LUDOWICI B.: Visualizing Uncertainty in Virtual Reconstructions. In *Proceedings of Electronic Imaging & the Visual Arts, EVA Europe '99* (Berlin, 1999), VASARI, GFaI, p. 16.
- [SPR*94] STROTHOTTE T., PREIM B., RAAB A., SCHUMANN J., FORSEY D. R.: How to render frames and influence people. *Computer Graphics Forum* 13, 3 (1994), 455–466.
- [SS02] STROTHOTTE T., SCHLECHTWEIG S.: *Non-Photorealistic Computer Graphics: Modeling, Rendering, and Animation*. Morgan Kaufmann, San Francisco, 2002.
- [vFL*00] VAN DAM A., FORSBERG A. S., LAIDLAW D. H., LAVIOLA, JR. J. J., SIMPSON R. M.: Immersive VR for scientific visualization: A progress report. *IEEE Computer Graphics and Applications* 20, 6 (Nov./Dec. 2000), 26–52.
- [VPW*04] VERGAUWEN M., PLETINCKX D., WILLEMS G., VERBIEST F., GOOL L. V., HELSEN T.: As time flies by: Mixed image and model-based rendering of an historical landscape from helicopter images. In *VAST 2004: Virtual Reality, Archaeology and Cultural Heritage* (2004), pp. 241–250.
- [War04] WARE C.: *Information Visualization: Perception for Design*, 2nd ed. Morgan Kaufmann Publishers, 2004.