Modeling Light Scattering for Virtual Heritage

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Computer graphics, in particular high-fidelity rendering, make it possible to recreate cultural heritage on a computer, including a precise lighting simulation. Achieving maximum accuracy is of the highest importance when investigating how a site might have appeared in the past. Failure to use such high fidelity means there is a very real danger of misrepresenting the past. Although we can accurately simulate the propagation of light in the environment, little work has been undertaken into the effect that light scattering due to participating media (such as dust in the atmosphere) has on the perception of the site. In this article, we present the high-fidelity rendering pipeline including participating media. We also investigate how the appearance of an archaeological reconstruction is affected when dust is included in the simulation. The chosen site for our study is the ancient Egyptian temple of Kalabsha.

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1. INTRODUCTION

Lately archaeological reconstructions have become common in television documentaries, film, and the publishing industries as part of presenting ancient cultures [http://www.cs.kent.ac.uk/people/staff/nsr/arch/visrcant/visrcant.html]. Recent advances in computer graphics, such as low-cost high-performance hardware or tools for efficiently handling datasets from laser scanners [Callieri et al. 2003], enable virtual reconstructions to become a valuable tool for archaeologists as a way of recording, illustrating, analyzing and presenting the results [Gutierrez et al. 2004b]. However, if we are to avoid misleading representations of how a site may have appeared in the past, then the computer-generated environments should not only look real, they must accurately simulate all the physical evidence from the site [Chalmers et al. 2002; Martinez 2001].

Realistic image synthesis is the process of computing photorealistic images which are perceptually and measurably indistinguishable from real-world images. The generation of photorealistic images has always been one of the major goals in computer graphics. In order to obtain these images, it is required that the underlying physical processes of materials and the behavior of light are accurately modeled and simulated [Dutré et al. 2003]. In many graphics applications, including virtual archaeology, it is also assumed that light travels through a nonparticipating medium, normally clear air or a vacuum. For a great majority of synthesized images, this is a satisfactory assumption. However, in some situations, it is necessary to include the participating media such as fog, smoke, dust, humidity, or clouds, to provide the required level of realism within the images, see Figure 1. In archaeological sites in particular, the materials used to provide interior light, for example, candles and wood fires, would have generated smoke, perhaps significantly affecting visibility in these environments [Rushmeier 1995]. High-fidelity computer graphics allow these effects to be investigated in a physically accurate, safe, an noninvasive manner [Devlin and Chalmers 2001].

In this article, we consider how physically-based participating media should be incorporated as one part in the reconstruction process when investigating how a site may have appeared in the past. We also investigate how the affect of participating media in the lighting simulation can alter the perception of a virtual reconstruction. The rest of the article is organized as follows. Section 2 presents related background work. In Section 3, we briefly discuss the basic theory behind participating media. Our chosen case study, the Kalabsha Temple in Egypt, is presented in Section 4 and the virtual reconstruction in Section 5. The results from our simulations including participating media are presented in Section 6. Finally, conclusions and future work are outlined in Section 7.

2. BACKGROUND

The popularity of virtual archaeology has led to a significant number of virtual reconstructions ranging from nonphotorealistic presentations, Quicktime VR images, realistic looking computer models, and augmented reality applications to fully reconstructed urban environments [Forte et al. 1997; Barceló et al. 2000; Vlahakis et al. 2001; Willmott et al. 2001; Dikaikou et al. 2003; Roussou and Orettakis 2003; Stumpfel et al. 2003; Gutierrez et al. 2004b]. Currently, many virtual reconstructions are limited because their level of realism cannot be validated. The generated images may look realistic, but their accuracy is not guaranteed since they have no physical basis in reality. In order for the archaeologists to benefit from computer-generated models and use them in a predictive manner, they must accurately simulate all the physical evidence from the site being reconstructed [Devlin et al. 2001]. The virtual reconstruction should not only be physically correct but also perceptually equivalent to the real scene it portrays [McNamara et al. 1998; Chalmers et al. 2002; Martinez 2001]. Simply put, if computer reconstructions are to go beyond mere digital images and models, and become a predictive tool for archaeologists, physically-based rendering techniques have to be used.

Fig. 1. Photograph of smoke in a medieval house in Sussex, showing the effects of participating media.

The high-fidelity rendering pipeline can be viewed in three stages; capturing of accurate geometry and materials, modeling the behaviour of light, and visual display. In the following, we will describe these three steps in further detail and discuss previous related work.

2.1 Geometry and Materials

Generating detailed 3D models with high accuracy has been made much easier with the use of laser scanning [Levoy et al. 2000; Bernardini et al. 2002; Fontana et al. 2002; Pollefeys et al. 2001; Stumpfel et al. 2003; Baracchini et al. 2004]. Normally, to acquire a 3D geometry from an artifact or a site, a number of scans are needed to gather the full geometry. These scans are referred to as *range maps* [Scopigno and Cignoni 2005]. The number of range maps needed depends on the object's surface area and the complexity of its shape. Scopigno and Cignoni [2005] give a good overview of the laser-scanning pipeline. Overall the pipeline deals with the acquisition of these range maps and their reassembling into one complete 3D representation. Within this process, several steps need to be taken into account. First the maps have to be aligned and merged into a single mesh. After that, mesh-editing algorithms are normally used to improve the overall quality of the reconstructed mesh. After this step, the complexity is normally reduced, for example, by producing different level-of-details (LOD) or multiresolution representations [Luebke et al. 2003]. This step makes the meshes more manageable to work with. The final step in the pipeline deals with the problem of mapping color to the mesh using, for example, textures acquired by the scanner or by taking additional photographs.

One of the biggest difficulties in the material acquisition process is identifying the surface reflection properties of the site or artifact. By only capturing and mapping photographs, the lighting apparent when the picture was taken is going to be included in the image. In this way, it is normally not possible to change the lighting conditions within the simulation to obtain a photorealistic image. Problems such as discontinuity in color and low-resolution textures are common. More accurate techniques, which is part of the realistic image-synthesis process, involves capturing the model of the bidirectional reflectance distribution function (BRDF)—which describes the reflection properties of surfaces—at each point of the site or artifact. This can be done using several different photographs and/or lighting conditions [Rushmeier et al. 1998] and measurements of subsurface scattering [Jensen et al. 2001]. A robust image-based measuring method that detects the different materials in the image and fits an average BRDF to each of them is presented in Jensen et al. [2001]. Although, in many reconstructions, it can be hard to access all parts of the real site and approximations have to be made, this can be done by, for example, measuring the surface reflection properties of a smaller part of the site, which is thought to cover the range of materials the site is made of [Debevec et al. 2004].

2.2 Modeling the Behavior of Light

The goal of modeling the behavior of light is to simulate its interaction with the matter (the objects) in the scene, thus producing realistic renderings while being able to predict the resulting intensity at any given point in the scene. Early local illumination models assumed that the shading (appearance) of each object was independent of the shading of any other object in the scene, which is obviously an oversimplification of the problem. Global illumination models, on the other hand, take into account the interaction between objects: a surface appearance will therefore depend on both the light sources and the appearance of the all the other surfaces visible from the first one.

Physically-based rendering methods allow us to accurately calculate with the distribution of light in the scene. The Radiance Equation, introduced in computer graphics by Kajiya [1986] and solved by most global illuminations algorithms, can only be used if a vacuum is the only medium in the scene where the interaction of light is completely nonexistent. But when rendering scenes that contain participating media, the interaction between the light and particles floating in the medium has to be taken into account. A physically accurate lighting simulation of such media implies solving the Radiative Transfer Equation (RTE) [Glassner 1994], which is an integro-differential equation and noticeably more complex. Further details on the modeling of participating media can be found in Section 3.

2.3 Displaying the Results

As explained, one of the goals of recreating cultural heritage sites is to obtain an image that provokes the same sensation to the viewer as if he/she were seeing the scene in the real world. Generally speaking, the objective of any synthetic, high-fidelity imagery is to exactly capture the visual appearance of the modeled scenes. Physically-based rendering methods allow us to accurately calculate the energy distribution in the scene. However, this exact calculation does not guarantee that the visual appearance of the displayed image matches the real scene; the range of luminances in a real scene usually surpasses, by several orders of magnitude, the range of the display device. Pictures in a newsletter have a maximum contrast of 30:1, CRT monitors have a standard range of up to 300:1, and only some high photographic-quality printings have ranges of 1000:1. However, in the real world, the dynamic range of illumination is on the order of 10,000:1. On the other hand, visualization conditions of the real scene and synthetic image rarely match. In addition, studies in human visual mechanisms have not come to a definitive model yet.

This brings up the need for tone mapping/reproduction since the range of luminance values in a real scene is almost always orders of magnitude greater than the range a computer display can show. Tone reproduction deals with the problem of mapping scene intensities to displays with limited dynamic range. This is an important part of the realistic image synthesis process. The typical input to tone mapping operators are global illumination images or high dynamic range (HDR) camera images [Reinhard et al. 2005].

For more than a decade, various tone-mapping operators have been introduced to try to solve this problem, although none is completely successful yet. A complete survey on tone-mapping techniques can be found in Devlin et al. [2002] and Reinhard et al. [2005], and an evaluation of some of them in Ledda et al. [2005]. It is important to highlight that the main problem of tone reproduction is the reduction of the contrasts in the image, maintaining its appearance. All the other effects, such as color sensitivity loss, visual acuity, chromatic adaptation and temporal responses directly depend on the selected solution to adapt the contrast.

As a tone mapper, we have used our implementation of Ward's algorithm in our own tone-mapping application called SEKER [Gutierrez et al. 2003]. It is also important to model the human visual system when displaying results as shown in Gutierrez et al. [2004a]. Several effects of the human visual system, such as color loss, veiling glare, or bleaching, have also been introduced in this work to enhance realism as described in Gutierrez et al. [2005a].

Recently, novel HDR monitors [Seetzen et al. 2004], using a series of LED backlights, have been produced which make it possible to display HDR images with additional luminance. Displaying imagery on these types of monitors makes it possible to obtain really black values in the same way as a sun simulation would give much brighter values than a conventional display. Although these monitors can display images with a 200,000:1 contrast ratio, they are still very expensive and not widely available.

3. PARTICIPATING MEDIA

Light traveling through participating media interacts not only with the surface of the objects but with the medium itself as well. The atmosphere, for instance, contains particles, aerosols, dust, etc., and light interacts with all of them. The color of the sky, the loss of visibility on a foggy day, the so-called aerial perspective (loss of color perception with distance), etc., are all effects of this interaction of light with the invisible particles of the atmosphere. Sometimes the influence of participating media can be ignored while producing an image, thus simplifying the rendering. But several phenomena cannot be simulated without taking these influences into account, and, in many cases, they are crucial for a realistic high-fidelity epiction of the scene being simulated. In fact, using one of the examples given before, aerial perspective is one of the most important depth cues in outdoors scenes. In this section, we are going to introduce a physically-based framework which will provide us with a better understanding of the phenomena involved.

The most important effects of this interaction, mainly scattering, are spatial and angular spreading of the incoming light, which greatly varies our perception of the scenes. Effects such as the glow around light sources or loss of color are due to the presence of these participating media, which causes light to be scattered while propagating.

To account for all those effects in the rendered images, the so-called integro-differential Radiative Transfer Equation (RTE) [Glassner 1994] needs to be solved. This equation governs light transport in participating media and is given by:

$$\frac{\partial L_\lambda(x,\vec{\omega})}{\partial x} = \alpha_\lambda(x) \cdot L_{e,\lambda}(x,\vec{\omega}) + \alpha_\lambda(x) \cdot \int_\Omega p_\lambda\left(x,\vec{\omega}',\vec{\omega}\right) \cdot L_\lambda(x,\vec{\omega}')d\vec{\omega}' - \kappa_\lambda(x) \cdot L_\lambda(x,\vec{\omega}').$$

To describe the radiance scattered in any given direction, phase functions, which formally represent the radiance scattered in a given direction divided by the radiance which would have been scattered in that direction had the scattering been isotropic, are used. A much more detailed discussion, including all the formulas and equations that lead to the Radiative Transfer Equation as well as strategies to solve it appears in Gutierrez et al. [2005b].

The way that participating media influences perception can be obvious or subtle. Objects might appear blurry and some detail might be lost. Light scattering and absorption are wavelength-dependent processes so color perception will also be changed. Under certain conditions, participating media can also act as light sources themselves or at least have a great influence in the contrasts and luminance gradients of a scene. As a consequence, the adaptation level[1] of the observer will effectively be altered, and therefore the way he/she perceives the scene will change. Several other effects that depend on luminance levels will be triggered as well such as color perception loss under low-light levels or a decrease of visual acuity.

4. CASE STUDY: THE TEMPLE OF KALABSHA

The ancient Egyptian temple of Kalabsha was chosen as a case study for our virtual reconstruction given that the sun was a key feature of Egyptian religion and the dust levels in Egypt are high [Sundstedt et al. 2004, 2005]. Using predictive light scattering, it is possible to study the perception of the site when the sun rays entering the temple are being scattered by dust particles.

The temple was the center of every ancient Egyptian community. This “House of Divinity” was the sacred model for the Egyptian world, maintained the harmony between Heaven and Earth, provided the focus for the Divinity of the Pharaoh, and served as the home for the local divinities [Arnold 1999; Jacobson et al. 2005]. The temple of Kalabsha is one of the last temples built for the ancient Egyptian gods. It is also the largest free-standing temple of the lower Egyptian Nubia located about 50km south of Aswan. The temple is built of sandstone masonry and dates back to the Roman Emperor Octavius Augustus, 30 BC, although the site it was built upon evidently dates back to the colony of Talmis, dated at least during the reign of Amenhotep II (1427–1400 BC) [Shaw and Nicholson 2002]. The temple was dedicated to the Nubian fertility and solar deity known as Mandulis and the walls are covered with text and inscriptions depicting Egyptian deities such as Isis and Osiris. The temple was originally built at Kalabsha (Talmis) but with the construction of the Aswan High Dam in 1959, it became apparent that the temple would disappear under the rising waters of the Nile. In order to save the monument, it was decided that Kalabsha was going to be dismantled and moved to a new site.

4.1 The Architecture

The design of the temple is classical for the Ptolemaic period (http://www.touregypt.net/kalabsha.htm), with pylon, courtyard, hypostyle hall, and a three-room sanctuary. The courtyard just inside the pylon once had columns on three sides. At either end is a staircase that leads to the pylon. The pylon is offset to the courtyard behind since it was constructed on the site of an earlier structure constructed by Ptolemy IX. The small rooms in the surrounding wall were used for storage. After the hypostyle hall are the three chambers, the pronaos, the naos or sanctuary where statues of gods were located, and the adyton which is the innermost or secret shrine. There is also a nilometer which was used to collect sacred water for the gods. Two further elements of religious importance remain outside the enclosure wall which is, in turn, narrowly enclosed by another (outer) enclosure wall. At the South West angle of this latter enclosure is the Mamisi where the sacred birth of the Pharaoh was

[1]The dynamic range of luminances in the real world reaches up to fourteen log units, whereas the optical nerve can only transmit 1.5 log units. We can adjust this limited range to the range of the scene through a process known as adaptation, perceiving data around that adaptation level. The process is easily explained by the following example. When we enter a dark room after being exposed to normal daylight luminance levels, we at first cannot distinguish any detail in the room since our adaptation level is that of the daylight scene but the room luminances are orders of magnitude below that level. As minutes pass by, though, we begin to distinguish the most salient features of the room since our adaptation level has changed to that of the room luminances. The inverse process happens when we go back to daylight levels and are momentarily blinded until, seconds later, our adaptation level changes again, and we regain normal vision.

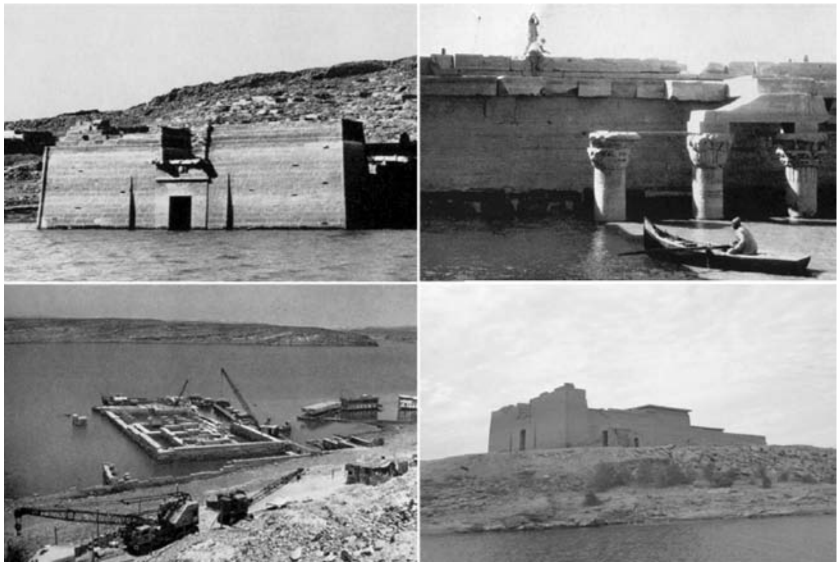

Fig. 2. The dismantling and reconstruction process [Wright 1972].

venerated. Finally one complete element of the earlier temple is preserved, the so-called Ptolemaic Chapel. The first enclosure wall is meant to bind an area of 66.08m $\times$ 33.04m. The original overall height of the Pylon was probably 16.25m (http://2terres.hautesavoie.net/kegypte/texte/kalabsha.html; http://www.touregypt.net/kalabsha.htm) [Curto et al. 1965; Wright 1972]. The temple itself was never finished and was therefore not as colorful as other temples from this period. The temple has some polychromy but much was destroyed when the temple was submerged by water. The architecture of the temple also shows unfinished details compared to other temples.

4.2 Saving the Site

In order to save the monuments, a project to move them to another site was launched. The parties responsible for the transfer were the German Nubian Committee, the Foreign Ministry of the German Republic, a German semi-governmental body for administrating foreign aid (GAWI), a major German Civil Engineering Firm (Hochtief) working with proper archaeological supervision [Wright 1972]. The work was started in 1961 by preparing the new site (Chellal) and recording the monument at old Kalabsha. Each dismantled unit from the old site was identified with a number and its position shown on detailed drawings. By December, it was impossible to work on the old site and the efforts were then focused on a storage place at the new site for the reerection. In 1962, a second season of dismantling was carried out and all 13,000 blocks were placed at the new site. In total, 20,000 tons of stone were dismantled and moved. In October 1962, the first blocks were reset on the new site until the rebuilding was completed in November 1963. The temple now stands 750m to the south of the Aswan High Dam. Figure 2 shows some pictures of the dismantling and reconstruction process. There were three requirements necessary for the new site in order to achieve a similar layout to what defines the Nile Valley and all things built there [Wright 1972]. First, the temple must face directly towards the Nile, that is, the longitudal axis must be set at right angles to the flow of the stream. In this way, the temple remains approximately east-west. Second, the monument must also be backed up by a rocky skyline to give the same appearance as other sites in the Nile Valley. Finally, the original level relative to the Nile waters must be approximately respected. If the reservoir of the High Dam were filled to

Table I. Position Coordinates for the Kalabsha Temple

	Old Location	New Location
LAT (DMS):	23 33′ 0N	24 4′ 60N
Lon (DMS):	32 52′ 0E	32 52′ 60E
Altitude:	172m	141m

the level proposed, the waters would rise to somewhere about the foot of the Quay. The new site was prepared so that it fulfilled all conditions. The latitude and longitude of the old and new location of the temple can be seen in Table I. These values can be used as input to the light model of the virtual reconstruction to study how the site might have been lit during a day at its original location.

4.3 Sun Worship

The sun was a key feature in ancient Egyptian religion, and therefore the position and orientation of the temple must be carefully chosen. The worship of the sun, although not associated with any certain time or place, received its greatest prominence in ancient Egypt. The daily birth, journey, and death of the sun was the dominating feature of life for the ancient Egyptians. For example, they used an analogy from their observations of nature, a beetle pushing a ball of dung along the ground, to express one aspect of the sun god. Since then, the scarab has continued to be an amulet of the sun in life and burial. It is often seen on the temple walls in Egypt [Quirke 2001]. The gateway of the Kalabsha temple also contains inscriptions of the disk of the sun as well as scenes of the king performing sacrificial rites and praying [Wright 1972]. Astronomy was used by the Egyptians to position their temples and pyramids accurately according to the sun. They also built temples to the sun which were aligned so that, at sunset of the summer solstice, the sunlight would enter the temple and make its way along the axis of the building to the sanctuary.

5. CREATING THE VIRTUAL TEMPLE

The first task in the virtual reconstruction process was to create a highly detailed geometric model of the temple of Kalabsha. Fortunately, when the temple was dismantled, it was very well documented, including detailed drawings and measurements so that it could subsequently be physically reconstructed. A three-dimensional geometrical model was created based on these architectural plans, visual measurements, and historical literature [Siegler et al. 1970; Wright 1972] using the Alias Maya modeling package. The model took two people several weeks to model with the more intricate parts, for example, the tops of the columns, taking the majority of the time. Although a more detailed model could have been created if laser scanning had been undertaken, the model currently consists of about 2.6 million polygons. For the purpose of studying the sunlight entering the temple, this model is sufficiently detailed. Furthermore, we were able to validate the geometry of our model with real measurements taken at the site.

Equally important to the geometric model is the representation of the materials which determines how the light interacts with the geometry. In fact, a key problem in creating the model was not so much the geometry, which was well documented when the site was dismantled, but determining the texture and surface properties of the stone. Measurements taken during a site visit in January 2003 confirmed the Lambertian nature of the stone, and thus we assumed a predominantly diffuse material. It was therefore not necessary to determine their precise BRDF using samples and a sophisticated device such as a gonioreflectometer. The results found in Debevec et al. [2004] were used as a basis for our simulations. The materials were modeled directly in Lucifer without any significant loss of accuracy. Lucifer is a spectral renderer, which can handle participating media in a physically-based manner, described indepth in Gutierrez et al. [2005b].

5.1 Illumination-Neutral Textures

The textures have been created based on the photographs taken on site. Since all photographs taken for the textures also contain the illumination in which the pictures were taken in order to acquire illumination-neutral textures, a piece of green card was introduced. This was important since we introduced our own simulated light in the reconstructions [Chalmers et al. 2002; Sundstedt et al. 2004]. The diffuse nature of the materials allowed us to take TIFF photographs with a static camera of materials with and without the green card. The spectral properties of the card under a known light source were determined previously using a Spectrophotometer. The illumination at each pixel of the photograph could then be corrected based on the equivalent pixel value of the green card photograph. In total, 21 different seamless textures were used for the environment with the largest resolution 2188×945, which was also repeated for larger areas. An alternative technique to the green card would have been to use a Macbeth Color chart and the program, macbethcal in Radiance [Larson 1997], to directly compute the correct color and brightness. Neither of these techniques is perfect and neither will work in the presence of highly specular or complex geometrical surfaces. However, for the diffuse surfaces of the temple, it enabled us to acquire a good approximation. Figure 3 shows two side-by-side comparisons of the temple as it stands today and the virtual reconstruction.

6. RESULTS

The new location and orientation of Kalabsha means that without computer graphics it would not be possible to visualize the effect of the sun on the temple as it would have appeared to the ancient Egyptians, Figures 4 and 5. By knowing the carefully chosen co-ordinates of the original location of the Kalabsha temple, we could place the computer model back virtually to where it was originally built. To study how participating media alters the perception of the Kalabsha Temple, we have chosen one of the inner three chambers. A sun simulation was made, including participating media in the form of suspended dust particles. To produce the simulations we used Lucifer [Gutierrez et al. 2005b]. The images have been rendered on a 4GHz CPU with 1GB of RAM, at PAL resolution (720×512 pixels), with an adaptive antialiasing of up to four rays-per-pixel. Obviously, including or not including participating media greatly affects rendering times from less than a minute per frame without it to an average of 34-minutes per frame including it. In the absence of participating media, all the space between the light sources and the geometry is ignored, and light only interacts with the surfaces of the objects in the scene. With participating media, on the contrary, light-matter interactions (with the atmosphere in this case) occur even as light travels from the source to the objects, and computations of such interactions need to be performed at each incremental step. On the other hand, Lucifer is a physically-based renderer, and no speed-up strategies are adopted if they compromise the quantifiable accuracy of the results. Other production-based renderers could cut many corners in the computations, reducing rendering times at the cost of physical accuracy.

The three rooms have only small windows high up on each wall for light to enter. This makes these rooms especially interesting since there is practically no direct sunlight entering, and thus the participating medium plays a key role in the transport of light throughout the scene. Photographs from other sites with similar architecture, see Figure 7(a), show how the sunlight scatters through participating media when entering the chambers, greatly altering the visual sensation they provoke. Figure 7 shows a close up of one of the modeled windows, with participating media (c) and without participating (b) participating media (b). It is evident how the sunrays play a key role in the perception of the scene. Figure 8 shows some frames of an animation of sunlight through a slit. Figure 6 shows the difference in how the interior of the Kalabsha temple might look with and without participating media. The presence of participating media in the simulation (dust from the sandy environment of the temple) creates a whole

Fig. 3. Real temple today and its virtual reconstruction. Top, the Pylon (main entrance); bottom, the pillars by the Pylon.

new luminance distribution and, what is more important, a very different gradient distribution, thus changing dramatically the perception of brightness. Colors and details are almost indistinguishable in the background since the eye is adapted to the higher luminance levels of the foreground.

7. CONCLUSIONS AND FUTURE WORK

This article has presented considerations that should be addressed when creating a virtual reconstruction including a participating medium. A case study was presented using a reconstruction of the ancient Egyptian temple of Kalabsha. One of the benefits with a high fidelity reconstruction is that it enables archaeologists to experiment with different hypotheses. For example, it is possible to study how different lighting conditions might have affected how the site was used. Sun simulations, in combination with an accurate geometric model, also allow Egyptologists to study how sunlight entered the temple with and without dust.

A future visit to Kalabsha is planned to measure the dust levels in the temple to validate the parameters chosen for our simulations. Since this work can be considered as a proof-of-concept, heuristic values for scattering and absorption coefficients have been used, along with a generic Henyey-Greenstein phase

Fig. 4. The Temple of Kalabsha: static sun position, rotating camera.

Fig. 5. The Temple of Kalabsha: static camera position, sun animation.

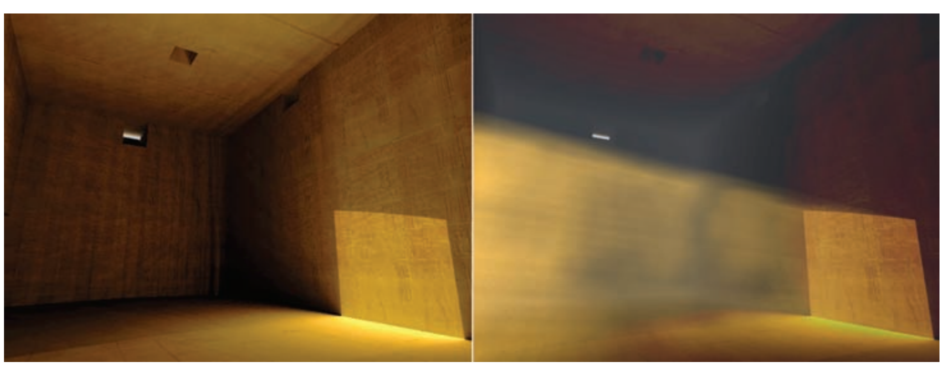

Fig. 6. Simulation of the interior of one of the chambers. Left: without participating media. Right: including participating media.

Fig. 7. Left: real picture of a slit. Middle: simulation without participating media. Right: simulation with participating media.

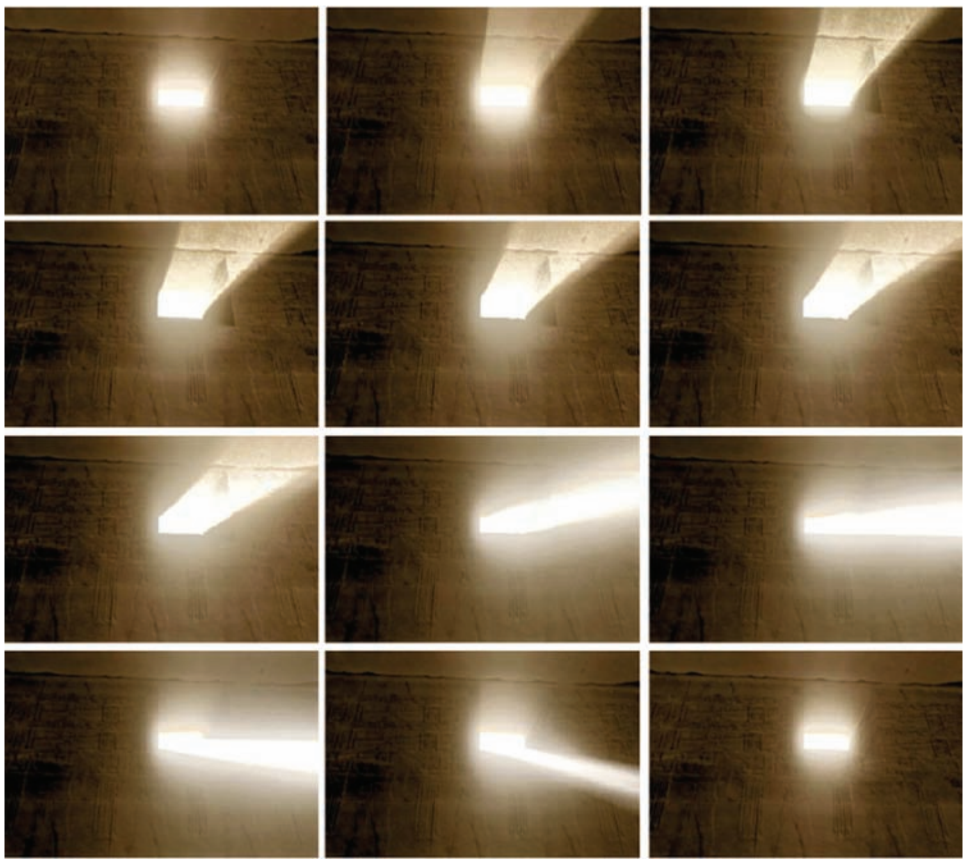

Fig. 8. Several frames of our animation of sunlight through the slit, at different times of the day.

function with varying values for the g parameter. Future experiments will also include smoke from torches or tapers, representations of which appear on the walls of the New Kingdom tombs and temples. There is no evidence found by Egyptologists for how lamps might have been positioned [Sundstedt et al. 2004]. Reconstructed lamps with olive and sesame oil would allow a study of how artificial lighting could have been used in addition to the illumination from the sun. Future work includes creating a flickering flame model that could produce smoke.

As explained before, the computational requirements for calculating the interaction of light with participating media are substantial. This process can take many minutes or even hours for one single image so accelerating these computations (without losing fidelity) should be a priority. Many times rendering efforts are spent on details which are not perceived by the viewer. Exploiting this fact, future work will explore how perceptual strategies, such as saliency information [Itti et al. 1998], can be incorporated in physically-based perceptual rendering of participating media. For example, saliency information informs us of what areas humans automatically attend to in a scene. From this, computation effort can be spent on improving details which are perceptually more important. A first step in this direction is presented in Anson et al. [2006]. An eye tracking device [Tobii 2005] could be used in the validation process to measure eye movements of human observers. This would give valuable information on how the inclusion of a participating media in the simulation can alter the way we look at a site. GPU and parallel-processing techniques are already being implemented in Lucifer. Finally, temporal coherence will be studied to speed up the rendering of animations.

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