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Participating Media for High-Fidelity Cultural Heritage

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Abstract

Computer graphics, and 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 has on the perception of the site. In this paper we investigate how the appearance of the interior of the ancient Egyptian Temple of Kalabsha is affected when including dust in the simulation. Given that the sun was a key feature of Egyptian religion, the correct perception of the sun rays entering the temple and being scattered by the dust may be important for a better comprehension of that culture.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual Reality I.3.8 [Computer Graphics]: Applications J.2 [Physical Sciences and Engineering]: Archaeology

1. Introduction

In many graphics applications, including virtual archaeology, it is assumed that light travels through a non-participating medium, normally clear air or a vacuum. For a great majority of synthesised 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 [Rus95]. High-fidelity computer graphics allows these effects to be investigated in a physically accurate and a safe, non-invasive manner.

Experimental archaeology and high-fidelity reconstructions, incorporating participating media in the lighting simulation, allow us to recreate the archaeological site and show how it may have been perceived in the past. Predictive light scattering also opens up new possibilities of exploring how past environments might have been perceived, allowing ar-

Figure 1: *Photograph of a smoky medieval house in Southampton.*

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chaeologists to investigate hypotheses concerning architecture, art and artefacts.

In this paper we consider how physically-based participating media should be incorporated when undertaking a reconstruction of a heritage site with a view to investigating how it 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 environment. The site we consider is the ancient Egyptian temple of Kalabsha [SCM04].

The rest of the paper is organised as follows. Section 2 presents related background work. In section 3 we briefly discuss the basic theory behind participating media. The importance of participating media in simulations for perception is stated in section 4. Our chosen case study, the Kalabsha Temple in Egypt, is presented in section 5 with the results presented in section 6. Finally, conclusions and future work are outlined in section 6 and 7 respectively.

2. Background

Lately computer graphics reconstructions have become commonplace in television documentaries, film and the publishing industries as part of presenting ancient cultures. Recent advances in computer graphics, such as low cost, high performance hardware, tools for efficiently handling data sets from laser scanners [CCG*03], etc., also enables virtual reconstructions to become a valuable tool for archaeologists as a way of recording, illustrating, analysing and presenting the results.

The popularity of virtual archaeology has led to a significant number of virtual reconstructions ranging from non-photorealistic presentations, Quicktime VR images, realistic looking computer models, augmented reality applications and even full reconstructed urban environments, for example [FSR97, BFS00, VKea01, WWAD01, DEC03, RD03, STH*03, GSM*04]. Currently, the value of three-dimensional computer reconstructions is limited because their level of realism cannot be guaranteed. 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 meaningful way, they must accurately simulate all the physical evidence from the site being reconstructed [DC01]. The virtual reconstruction should not only be physically correct but also perceptually equivalent to the real scene it portrays [MCTR98,CDB*02,Mar01]. In a word, if computer reconstructions are to go beyond mere digital images and models, becoming a true tool for archaeologists, physically-based predictive rendering techniques have to be used, along with adequate tone mapping mechanisms to ensure the image is perceptually accurate on the display device.

3. Modeling participating media

When rendering archaeological scenes which include dust, smoke, fog, soot, etc. it is also necessary to take into account the scattering of light as it passes through the medium. All these effects are essential for a physically accurate lighting simulation. This process involves solving the radiative transport equation (an integro-differential equation), which is more complicated than the traditional rendering equation solved by global illumination algorithms [Gla95]. This section introduces the basics principles of light transport in participating media, but it is not meant to be exhaustive. For a more complete overview including different resolution strategies the reader can refer to [PPS97].

Light travelling through participating media interacts not only with the surface of the objects, but with the medium itself as well, see Figure 2. Four new types of interaction occur: emission, absorption, in-scattering and out-scattering. The coefficients that govern these interactions are wavelength-dependent, and therefore the equation describing the variation of radiance L in a point x in the direction w must be written in its wavelength-dependent form (equation 1):

$$\begin{aligned}\frac{\partial L_\lambda(x,\vec{w})}{\partial x} &= \alpha_\lambda(x)L_{e,\lambda}(x,\vec{w}) + \sigma_\lambda(x)L_{i,\lambda}(x,\vec{w}) - \\ &\quad -\alpha_\lambda(x)L_\lambda(x,\vec{w}) - \sigma_\lambda(x)L_\lambda(x,\vec{w})\end{aligned} \quad (1)$$

where α is the absorption coefficient, σ is the scattering coefficient, L_e is the emitted radiance and L_i is the in-scattered radiance. We can group the last two terms of equation 1, which refer to absorption and out-scattering, into a single *extinction* term $\kappa_\lambda(x)L_\lambda(x,\vec{w})$, where the extinction coefficient is defined as:

Figure 2: *Photograph of volumetric light in an Egyptian temple.*

$$\kappa_\lambda(x) = \alpha_\lambda(x) + \sigma_\lambda(x) \tag{2}$$

The in-scattered radiance $L_{i,\lambda}$ depends of the radiance L_λ coming from all possible directions $\overrightarrow{w}$ over the sphere Ω. This in-scattered radiance can therefore be obtained by integrating over the whole sphere, thus:

$$L_{i,\lambda}(x, \overrightarrow{w}) = \int_\Omega p_\lambda(x, \overrightarrow{w}', \overrightarrow{w}) L_\lambda(x, \overrightarrow{w}') d\overrightarrow{w}' \tag{3}$$

Inserting equations 2 and 3 into equation 1 we obtain the so-called integro-differential Radiative Transfer Equation (RTE), which governs light transport in participating media [Gla95].

$$\begin{aligned} \frac{\partial L_\lambda(x, \overrightarrow{w})}{\partial x} &= \alpha_\lambda(x) L_{e,\lambda}(x, \overrightarrow{w}) + \\ &+ \sigma_\lambda(x) \int_\Omega p_\lambda(x, \overrightarrow{w}', \overrightarrow{w}) L_\lambda(x, \overrightarrow{w}') d\overrightarrow{w}' - \\ &- \kappa_\lambda(x) L_\lambda(x, \overrightarrow{w}) \end{aligned} \tag{4}$$

To describe the distribution of scattered light in the medium, so called phase functions are used. They 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:

$$p(x, \overrightarrow{w}', \overrightarrow{w}) = \frac{dL(x, \overrightarrow{w})}{\frac{1}{4\pi} \int_{\Omega_{4\pi}} L(x, \overrightarrow{w}') d\overrightarrow{w}'} \tag{5}$$

Different from the BRDF for surfaces, the integral of the phase function over the whole domain is adimensional and normalized. The most common geometry to describe phase functions is small homogeneous spheres, suspended in the medium, each one reflecting light diffusely according to Lambert's law. However, desert dust is made of more than a hundred different types of particles, each oriented in random directions, thus making its characterization a much more difficult task. A good reference and source of data to model dust properties can be found in [Kah03].

4. Participating media in perceptually-based rendering

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. This raises the need for tone 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. Many different techniques have been developed to try to solve this problem, although none is completely successful yet. A complete survey on tone mapping techniques can be found in [DCWP02] and an evaluation of some of them in [LCTS05].

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 having been exposed to normal daylight luminance levels, we 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 can start distinguishing 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 luminance levels and are momentarily blinded, until seconds later our adaptation level changes again and we regain normal vision.

The human visual system is very good at judging brightness, which is a subjective sensation, instead of luminance, which is the objective physical magnitude of the light energy. The perception of the brightness of an object depends on the contrasts around it: a dimly lit object will appear much brighter against a dark background than against a light background. This effect is closely related to the adaptation mechanism explained above.

The way participating media can alter the perception of things can be obvious or more 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 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 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.

5. Case study: the Temple of Kalabsha

The site chosen for our study is the ancient Egyptian Temple of Kalabsha. For the convenience of the reader, we repeat the historical background from [SCM04]. The temple of Kalabsha is the largest free-standing temple of Lower Egyptian Nubia located about 50 km south of Aswan and built of sandstone masonry. The temple dates back to the Roman Emperor Octavius Augustus, 30 BC, but the colony of Talmis evidently dates back to at least the reign of Amenhotep II in 1427 - 1400 BC [SN02]. The temple was dedicated to the Nubian fertility and solar deity known as Mandulis and the walls are covered with text and inscriptions depicting Egyp-

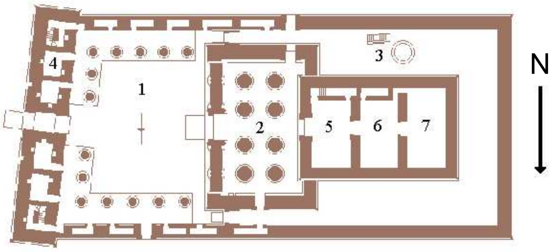

Figure 3: *Plan view of Kalabsha.*

tian deities such as Isis and Osiris. The temple itself was never finished.

The design of the temple is classical for the Ptolemaic period, Figure 3, with pylon (4), courtyard (1), 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 built on the site of an earlier structure built by Ptolemy IX. The small rooms in the surrounding wall were used for storage. After the hypostyle hall (2) are the three chambers, the pronaos (5), the naos (6), or sanctuary where statues of gods were located, and the adyton (7), which is the innermost or secret shrine. There is also a nilometer (3), 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 is 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 x 33.04m. The original overall height of the Pylon was probably 16.25m [CMRB65, Wri72].

5.1. Dismantling the Temple of Kalabsha

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.

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 [Wri72].

By August 1961 all the necessary contracts were signed and those to be engaged were assembled and housed at Aswan in September 1961. Work on preparing the new site (Chellal) began immediately and the works flotilla for operations on the Temple proceeded upstream to old Kalabsha on September 19th to begin the work of recording the monument. All necessary records were established so that the first blocks were dismantled on November 17th 1961. The various units of masonry were each identified with a number, and their position shown on a measured drawing. The blocks were then broken from the bond and removed from the wall. Dismantling continued day and night until December 9th when the rise of the Nile made further work impossible at the old site. All resources were then transferred to the work on developing the storage place and the new site for the re-erection of the Temple.

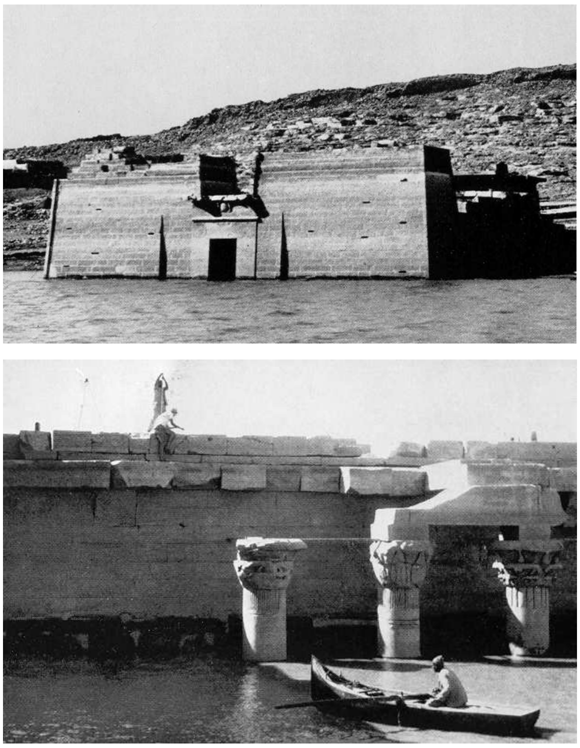

Figure 4: *The temple of Kalabsha in water at the old site: (top) exterior view of the pylon, (bottom) exterior view of the courtyard [Wri72].*

A second season of dismantling was carried out at the old site during May to October 1962 and completed so that all blocks scheduled for re-erection were transported and ranged in order at the storage place by the new site, where they were consolidated as necessary. Some 13,000 blocks, and in total 20,000 tons of stone were dismantled. On October 30th 1962 the first blocks were reset at the new site and the work of re-building was carried out continuously with day and night shifts until it was completed in November 1963. The temple now stands 750m to the south of the Aswan High Dam.

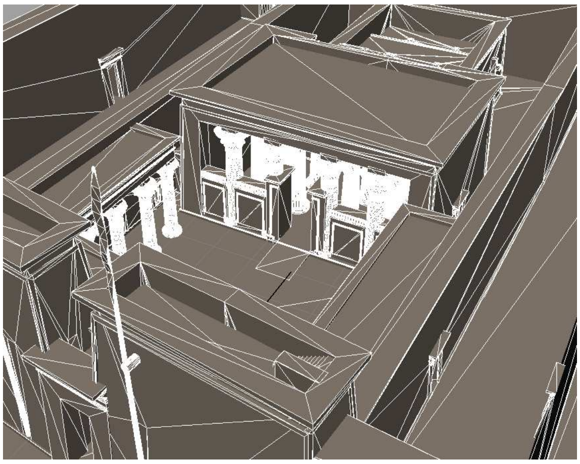

Figure 5: *Exterior view of the virtual temple in Alias Maya without textures.*

5.2. Reconstruction of the Kalabsha Temple

The first task in the virtual reconstruction process was to create a highly detailed geometric model of the temple of Kalabsha, see Figure 5. 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 [SR70, Wri72] using the Alias Maya modelling package. Although a more detailed model could have been captured if laser scanning would have been undertaken, the model currently consists of ~ 2.6 million polygons. Typically it takes many months to get laser scanning permission and for the purpose of our simulation the model is sufficiently detailed.

Equally important to the geometric model, is the representation of the materials, which determines how the light interacts with the geometry. The materials of the temple are predominantly diffuse, so it was not necessary to accurately determine their precise Bidirectional Reflectance- Transmittance Distribution Function (BRTDF) using samples and a sophisticated device such as a gonioreflectometer. The materials were modelled directly in Lucifer without any significant loss of accuracy. Lucifer is a spectral renderer, described in-depth in [GMAS05].

The textures have been created based on the photographs taken on site. Since all photographs taken for the textures also would contain the illumination in which the pictures were taken, in order to aquire illumination-neutral textures, a piece of green card was introduced. This was important since we introduced our own simulated light in the reconstructions [CDB*02, SCM04]. The diffuse nature of the materials allowed us to take TIF photographs, with a static camera, of materials with and without the card. The spectral properties of the card under a known light source were determined previsouly 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 being 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* [LS98] to directly compute the correct color and brightness. Neither of these techniques is perfect and will not work in the presence of highly specular or complex geometrical surfaces, however, for the diffuse surfaces of the temple, it enables us to acquire a good approximation of illumination-neutral textures.

5.3. Sun worship

We chose the Kalabsha Temple as our case study due to its direct relation with the visualization of participating media, specifically sunrays entering the temple. The sun was a key feature of ancient Egyptian religion. The worship of the sun, although not peculiar to any one time or place, received its greatest prominence in ancient Egypt. There, the daily birth, journey, and death of the sun was the dominating feature of life.

To express one aspect of the sun god, the Egyptians used a humble analogy from their observation of nature, the beetle pushing a ball of dung along the ground. The scarab has continued to be a solar amulet in life and burial and are commonly depicted on temple walls in Egypt [Qui01]. The gateway of the Kalabsha temple also contains inscriptions of the disk of the sun as well as scenes of the king giving sacrifices and praying [Wri72].

Astronomy was used by the Egyptians to accurately position their pyramids and temples. The ancient Egyptians also built sun temples that were aligned so that at sunset of the summer solstice, sunlight would enter the temple and make its way along the axis of the building to the sanctuary. These sun temples helped in determining the length of a year because the sun would only penetrate the temple in that way once per year.

6. Results

The new location and orientation of Kalabsha means that without computer graphics it would not be possible to vi-

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

Table 1: *Position coordinates for the Kalabsha Temple.*

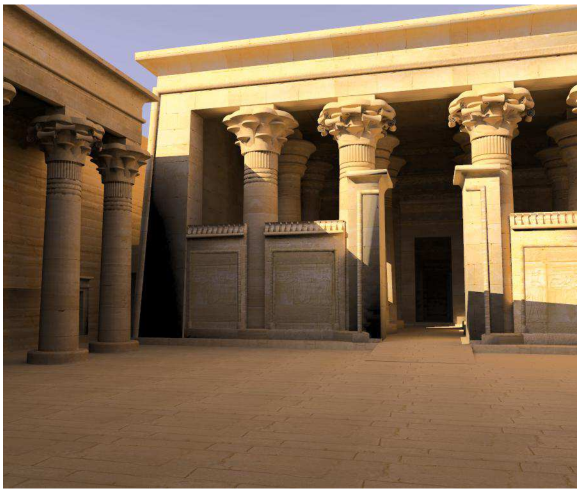

Figure 6: *High-fidelity reconstruction and sun simulation of the ancient Egyptian temple of Kalabsha rendered in Radiance using a daylight data derived from Commission Internationale de l'Eclairage (CIE) standards [LS98].*

sualise the effect of the sun on the temple as it would have appeared to the ancient Egyptians. By knowing the carefully chosen co-ordinates of the original location of the Kalabsha temple, see Table 1, this allows us to place the computer model back to where it was originally built. A sun simulation can then be made to study how the light shines on the temple and its interior during a day in 30 BC, see Figure 6.

But to accurately recreate how the sunrays looked inside the temple, we also need to incorporate participating media in our simulations, in the form of dust. The perception of the interior changes dramatically when this usually overlooked element is added, and it more closely reassembles the look it might have had two millennia ago.

We have chosen one of the inner three chambers for our investigation of how participating media might alter the perception of the Kalabsha Temple. The three rooms have only got small windows high up on each wall for light to enter through them. This makes these rooms especially interesting since there is practically no direct sunlight entering there, 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 2, show how the sunlight scatters through participating media when entering the chambers, greatly altering the visual sensation they provoke.

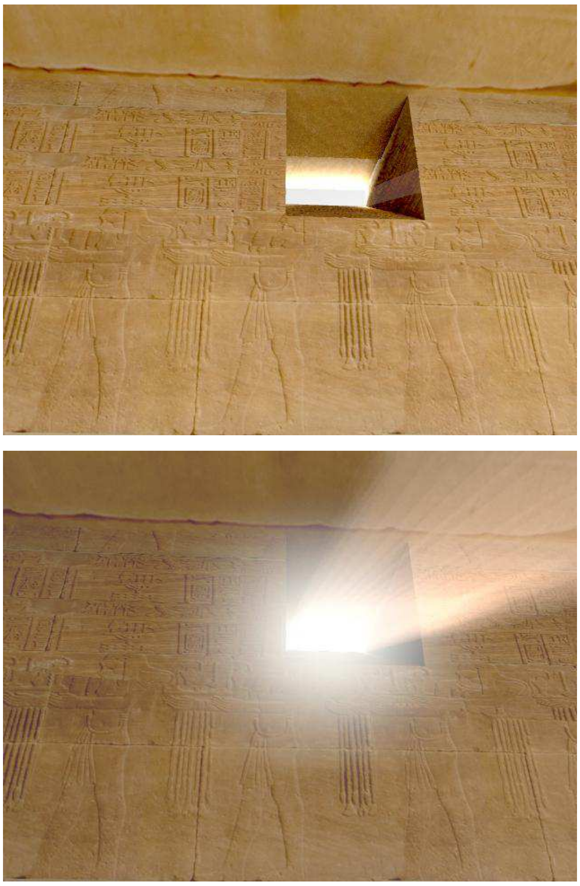

Figure 7: *Visual comparison of two renderings of one interior window of the Kalabsha temple rendered in Lucifer: (top) without participating media, (bottom) with participating media.*

Figure 7 shows a close up of one of the modeled windows, with and without participating media. It is evident how the sunrays play a key role in the perception of the scene. Figure 8 shows the difference in how the interior of the Kalabsha temple might look with and without taking into account participating media. The presence of participating media in the simulation (dust from the sandy environment of the temple) creates a whole 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

In this paper we have showed the importance of rendering an archaeological site with physically-based lighting which incorporates participating media. This technique provides a safe and controlled process in which the archaeologists can experiment with different hypotheses concerning the lighting conditions present, with and without a participating medium, and how this could have affected site utilisation.

It has been shown how modeling participating media in

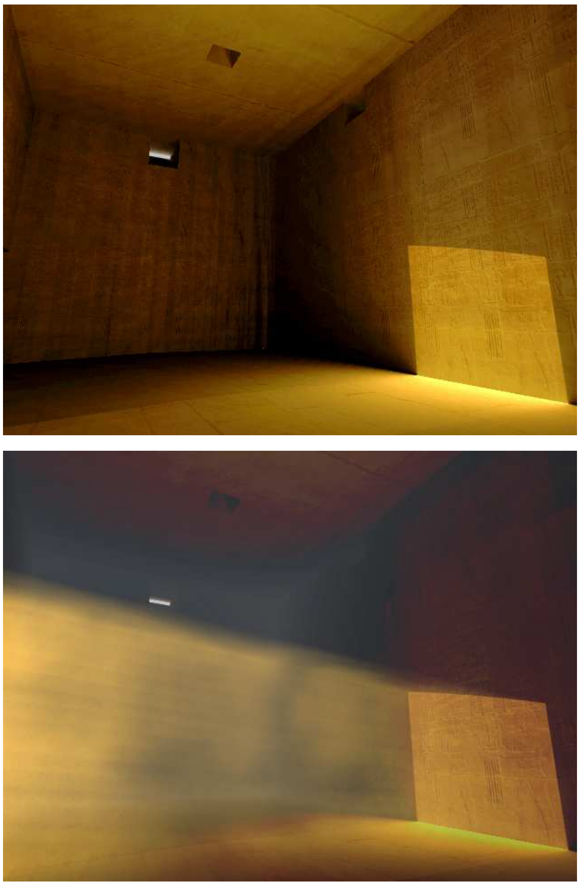

Figure 8: *Visual comparison of two renderings of the interior of the Kalabsha temple rendered in Lucifer: (top) without participating media, (bottom) with participating media.*

certain environments can greatly affect the way something is perceived. In the field of cultural heritage, where most of the digital reconstructions are done to show the public how a certain building or site may have looked like, or to better understand certain aspects of them, misrepresenting the past might lead to the wrong conclusions.

8. Future work

While physically-based participating media is a must in certain applications, simulating it is a very computation expensive process. Shortcuts that fail to reproduce the exact phenomena involved might again lead to misinterpretations of the past. We are currently concentrating on perceptual techniques to distribute rendering accuracy based on a previous knowledge of how the observer would see the real scene under the conditions of the simulation.

A future visit to Kalabsha is planned to measure the dust levels in the temple to validate the dust levels chosen for our simulations. Future experiments will also include smoke from torches or tapers which are known from representations on the walls of the New Kingdom tombs and temples. Furthermore, the use of an eyetracking device would allow us to measure involuntary eye movements and attention shifts, which could tell us more about the areas of the temple that are emphasised under different simulation conditions. We also intend to extend our simulations to exterior images, including atmosphere and dust scattering.

Finally, we plan on extending our simulations to underwater archaeology. Water is a very thick participating medium, where lots of interactions with light occur. Depending on its characteristics, its hue and visibility can change greatly, thus altering the perception of the underwater site. Once again, by using a physically-based model of water we can extend the scope of the simulations to predictive tasks, such as planning dives or rescue missions.

9. Acknowledgements

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Figure 9: *(top left) High-fidelity reconstruction and sun simulation of the ancient Egyptian temple of Kalabsha rendered in Radiance, (top right) photograph of volumetric light in an Egyptian temple, (bottom) visual comparison of two renderings of one interior window of the Kalabsha temple rendered in Lucifer: (left) without participating media, (right) with participating media.*