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The Virtual Reconstruction and Daylight Illumination of the Panagia Angeloktisti

Jassim Happa[1†], Alessandro Artusi[2,1], Piotr Dubla[1], Tom Bashford-Rogers[1], Kurt Debattista[1], Vedad Hulusić[1], and Alan Chalmers[1]

[1] International Digital Laboratory, University of Warwick, UK
[2] CASToRC Cyprus Institute, Cyprus

Abstract

High-fidelity virtual reconstructions can be used as accurate 3D representations of historical environments. After modelling the site to high precision, physically-based and historically correct light models must be implemented to complete an authentic visualisation. Sunlight has a major visual impact on a site; from directly lit areas to sections in deep shadow. The scene illumination also changes substantially at different times of the day. In this paper we present a virtual reconstruction of the Panagia Angeloktisti; a Byzantine church on Cyprus. We investigate lighting simulations of the church at different times of the day, making use of Image-Based Lighting, using High Dynamic Range Environment Maps of photographs and interpolated spectrophotometer data collected on site. Furthermore, the paper also explores the benefits and disadvantages of employing unbiased rendering methods such as Path Tracing and Metropolis Light Transport for cultural heritage applications.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.3]: Picture/Image Generation -Display Algorithms—Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism - Color, Shading, Shadowing, and Textures—Computer Graphics [I.3.8]: Applications—

1. Introduction

High-fidelity virtual reconstructions of cultural heritage sites are becoming increasingly important for cultural heritage preservation, educational and research purposes. They are used by academics, museums, and media to visualise the appearance of the sites for various periods in time. Physically-based 3D virtual reconstructions may be used for the study of existing or ruined cultural heritage environments under user-defined conditions. This may in turn enable archaeologists to interpret and deduce new knowledge about the past.

In this paper, we present a virtual reconstruction of the Panagia Angeloktisti; a Byzantine church located in the Kiti region, in the south east of Cyprus. We investigate methods to recreate interior daylight for the model through Image-Based Lighting (IBL) [Deb98] using High Dynamic Range (HDR) environment maps from HDR photographs, but also by generating new HDR environment maps from a sparse set of spectrophotometer data [Pho08].

† e-mail: j.happa@warwick.ac.uk

Technical limitations in both light data capture and display technologies prevent the accurate presentation of low lit sites. However, with the use of HDR imaging [DM97, Deb98] and HDR displays systems [SHS*04], it is possible to study dark cultural heritage environments such as the Panagia Angeloktisti, in order to reconstruct and study them in a visually correct manner [ZCBRC07]. Our motivation is to widen the understanding of interior illumination for enclosed cultural heritage environments such as this church. We also investigate the immediate advantages and disadvantages of using unbiased rendering for cultural heritage environments. The purpose of this paper in particular is to identify key aspects to consider when relighting interior cultural heritage virtual reconstructions with outdoor daylight.

The remainder of the paper is organised as follows. Section 2 presents related work. Typical characteristics that need to be addressed for reconstructions of Byzantine environments are detailed in section 3. Section 4 presents the model itself and the reconstruction approach. The illumination models implemented for this paper are presented in section 5. Section 6 explains the rendering techniques em-

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ployed, while section 7 discusses the results of our renders. Finally, conclusions and future work are discussed in section 8.

2. Related Work

Virtual reconstructions today may opt for simplified geometry, material and light models to convey a rough estimate of the appearance of the environment. Simple lighting models may lead to reduction in reconstruction and rendering time, however may also lead to misrepresenting the scene. There has already been significant research conducted that points out the importance of correct use of interior lighting in high-fidelity computer graphics for virtual archaeology [RS04,SGGC05,ZCBRC07]. While these works discuss the simulation of light and its significance for cultural heritage reconstruction, they do not include detailed acquisition of sunlight data from the site to include with the illumination model of the interiors of the reconstruction.

There are several methods to model outdoor illumination. One approach is Image-based Lighting (IBL) [Deb98] through HDR photography [DM97, STJ*04]. In the cultural heritage domain, the virtual reconstruction of the Parthenon [DTG*04, Deb05] is perhaps the most well-known example to date that makes use of HDR photography IBL sky illumination. Another method is to assign known light data to windows and doors, and then project this light as light sources, for example as *mkillum* does in Radiance [WS98].

A third method includes simulating the physical sky by considering the sun and lighting the geometry model using a latitude and a longitude position on Earth. The *gensky* program in Radiance for instance, produces a sky derived from the Commission Internationale de l'Eclairage (CIE) standard sky distribution at the given date and local standard time [WS98]. An example of the use of this approach is the reconstruction of the Egyptian Temple of Kalabsha [SCM04]. Several commercially available physically-based sky models are already available in most common rendering packages, including Mental Ray [Men07], (see Figure 10).

3. Byzantine Environments

Byzantine churches on Cyprus were mostly made of stone from nearby quarries and appear plain of the exterior. No paint was added to decorate the rough stone walls, and the lack of large windows adds to the compact characteristics of the buildings. This stands in direct contrast to the extensively decorated interiors with their abundance of highly-ornate sacral artwork and precious materials [HJK96].

From a virtual reconstruction standpoint, Panagia Angeloktisti stands out among the churches on Cyprus for primarily two reasons: Firstly, it is a church that has vastly changed its architectural features due to renovation work since it was first built in Byzantine times to the 1950s [Fou04]. While the Byzantine architecture style may have been of overall provincial influence from the Byzantine capital - Constantinople, there is also the possibility of individual characteristics in Byzantine churches specific to Cyprus [Cur00]. Based on the physical evidence left at the churches today, we must also consider the fact that the churches on Cyprus were and are susceptible to potential damage from earthquakes, and how this may have influenced architectural features. Continuous preventative building and rebuilding of church walls, meant that in time, the buildings lost some of their original interior appearance in favour of increasingly bulkier, enclosed form.

Secondly, the Panagia Angeloktisti, compared to other Byzantine churches on Cyprus, has fewer wall frescos, but its mosaic is richly decorated with gold tesserae. In this paper all gold-like reflective surfaces have been approximated using the Ward Bi-directional Reflectance Distribution Function (BRDF) model [War92].

3.1. Investigating Lighting Inside the Church

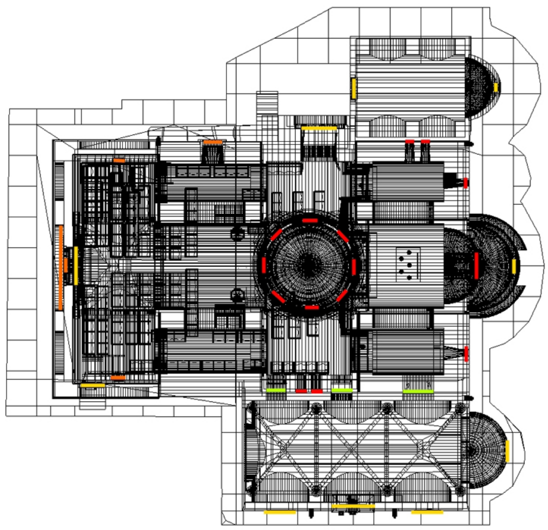

Figure 1: *Light source location diagram. Yellow: Ground floor. Orange: First floor. Red: Top windows. Green: Interior windows and doors.*

Byzantine churches on Cyprus have small windows, and the geometry is enclosed. This makes the interior overall significantly darker compared to several other types of Christian churches. Figure 1 shows the locations where the light is coming from the outside. Yellow indicates the light coming from windows and doors at the ground floor. Orange signifies the light coming from the first floor, while the red signifies areas in which light enters the church from the top, what can be considered the second floor. Green highlights the areas that are interior windows and doors. These are openings to other sections inside the church, that allow sunlight to pass through to the main section.

The interior illumination was likely designed to provide people inside with a dramatic visual effect aimed at engaging the viewer to approach God [PEE04, ZSMA07]. It can therefore be argued that the original church was built to reflect lighting in a manner that gives the perception of a holistic environment. It is believed the upper parts of the church symbolically represented heaven and were therefore better lit from the dome than the lower parts. In early Byzantium this was achieved with the aid of daylight through small openings in the upper parts of the walls as well. From middle Byzantium however, the buildings had less openings letting in natural light and these were replaced by oil lamps and candles [The01].

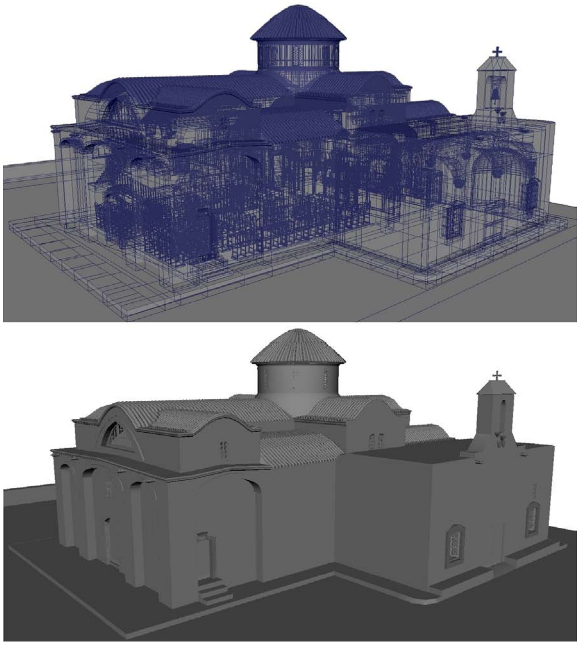

Figure 2: *Top: Wireframe. Bottom: Flat Shaded.*

4. Reconstructing the Panagia Angeloktisti

The Panagia Angeloktisti is still in use today. Tourists and visitors frequently enter the church to admire or pray inside. To estimate and model the walls and ceiling geometry, a laser distance meter [Lei07] was used to acquire the height values which were useful in the modelling stage of the project. This approach was chosen to avoid disrupting the everyday events at the church. The 3D reconstruction was manually modelled using Autodesk Maya 8.5 [Aut07], and rendered using in-house implementations of existing rendering algorithms such as Path Tracing [Kaj86] and Metropolis Light Transport [VG97]. Mental Ray [Men07], a rendering package that exists within Maya was also used. This is further discussed in Section 6.

Two types of camera equipment were used; conventional DSLR cameras and a SpheronVR [Sph07]. A Spectrophotometer [Pho08] was employed to measure chromaticity (XYZ) and spectral radiance (wavelengths) values of the sky. This data is often used to analyse and display colours of materials. Measurement tape was used for more accessible objects such as icons, chairs and ornaments found inside the church.

Photographs were primarily used to model the geometry shapes and details as there were no references such as blue prints available. However, they also aided in understanding how light changes in the interior of the church during the day. These photographs were taken in an as naturally diffusely lit environment as possible. The texture maps were carefully captured avoiding light from light bulbs, shadows, specular artefacts, caustics and colour bleeding.

Throughout the process of reconstructing the environment, continuous cross-referencing material that might indicate errors were taken. This involved anything from the visual materials captured earlier, such as photography, but also input from experts and local caretakers. Figure 2 shows a perspective view of the finished model in wireframe and flat shaded.

5. Illuminating the Church

Interreflection of sunlight is a large portion of the total illumination for most interior cultural heritage environments. The only additional light would come from flame light such as candles and oil lamps. While the visual perception of flame light most likely had a significant impact for Byzantine art [ZCBRC07], the majority of light inside the church does not come from these flames. Exterior and interior sunlight illumination is investigated. HDR Environment Maps, HDR DSLR Photography and spectrophotometer data of the sky were used in the process of relighting the church.

5.1. Capturing HDR environment maps

HDR environment maps were captured using the SpheronVR camera [Sph07] in the latitude-longitude panoramic format [BN76]. Due to inaccessibility to the roof of the church and lack of taller buildings in the nearby area, the environment maps were acquired at approximately ten meters distance from the main southern entrance. Here, there was a great distance to any other large object, yet it still remained as physically close to the church as possible. This approach also captured as much of the sky as possible.

Between 5:30 and 09:00 an environment map was captured every 30 minutes due to the vast changes in light. Between 09:00 and 17:00 one environment map was acquired every hour. After 17:00 to sunset at 20:30, the process was repeated every 30 minutes again. Figure 3 shows the first, mid-day and last capture during the outdoor capturing day,

Figure 3: *3 of 24 HDR Spherical Panoramas taken on June 18th, 2008 outdoors. Here in top-down order: a) sunrise (05:30), b)12:00 & c) sunset (20:20).*

Figure 4: *3 of 12 of HDR Spherical Panoramas taken inside the church on June 19th, 2008. Top: first floor, Middle: ground floor, centre of the building, Bottom: altar area.*

June 18th, 2008. Indoor spherical panoramas were acquired for reference purposes at mid-day on the 19th June 2008, see Figure 4.

5.2. DSLR Camera - HDR Photograph

The purpose of having HDR photographs was as a reference against which the rendered images could be compared. Locations with strong difference of contrast in light inside the church were considered. The selected photograph is shown in Figure 5. Its location is below the church dome, facing the north entrance of the church. This photograph was deemed the most appropriate due to the presence of direct and indirect illumination from inside and outside the church. It was taken at mid-day on 19th June, 2008. Figure 6 shows the orientation of the church in relation to Cardinal directions.

Figure 5: *HDR photograph of the north entrance.*

5.3. Creating a Skydome from Spectrophotometer Data

The spectrophotometer used was set to acquire and average 10 individual samples for each of the single 8 measurement values. Each of the 10 samples took less than a second to measure. The samples were averaged as the sky area measured is not a single point, but a rather large area in space. On average, the time between M1 and M8 was less than 5 minutes apart. Figure 6 illustrates locations of where spectrophotometer data was acquired. The device was mounted on a tripod, then aimed at a 45° angle towards the sky, away from the church.

An outdoor skydome HDR environment map was created from the eight measured spectrophotometer values. The values were first converted from XYZ to RGB (although from spectral radiance to RGB is also an option). Then, a nearest-neighbour interpolation of the eight RGB values was computed for all other neighbouring pixels in the generated environment map. The map is of the same pixel resolution as the HDR photograph. Figure 7 shows the output HDR environment map produced using the interpolation approach.

Environments lit with predominantly blue values inherently renders the scene considerably blue. This is due to the

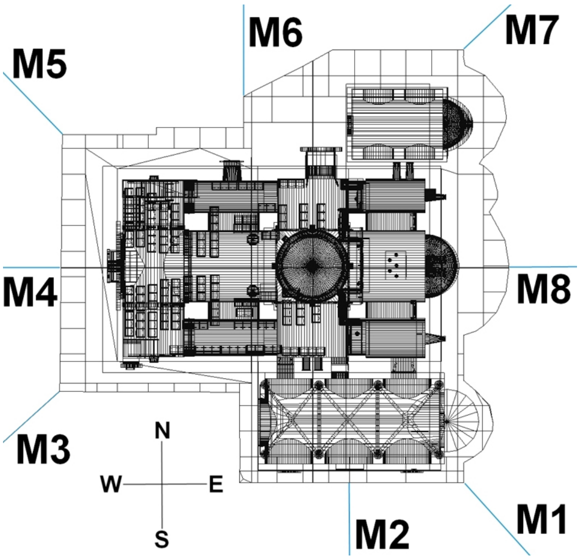

Figure 6: *Church orientation and locations of where spectrophotometer data was captured from, each aimed at a* 45° *angle towards the sky.*

Figure 7: *The generated HDR image with spectrophotometer values at 12:00.*

absence of the sun. Light values deviate significantly in the area occupied by the sun because of its vast brightness compared to the rest of the image. In the HDR photograph, the sun has close to an exponential growth in light values expressed as an ellipse. The sun values are therefore approximated and placed into the environment map based on the RGB values found in the HDR photograph in order to compensate for the much brighter light values. Figure 8 illustrates this point by showing the approximated sun along with the photographed sun at various exposure levels. The same was done for the ground bricks in the lower section of the image in Figure 7.

6. Rendering

To render physically-based images in computer graphics, it is necessary to solve the rendering equation [Kaj86]. This

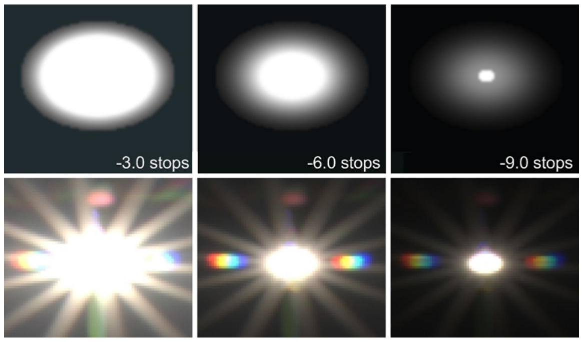

Figure 8: *The approximated sun based on an exponential growth compared to the same exposures in the HDR photograph, shown at various exposure levels.*

equation contains an integral which is difficult to solve analytically, generally requiring numerical methods such as Monte Carlo integration. By numerically integrating a function $f(x)$ using Monte Carlo methods, it is possible to draw N random samples of x and evaluate $f(x)$ at each point x. The estimated value of the integral is the sum of the evaluations of f divided by the total number of samples taken N. It can be shown that this estimate of the integral approaches the actual value as N tends to infinity. As the expected value of the error is zero, the method is said to be unbiased. This results in images that appear noisy and grainy at first, but will eventually converge to the correct solution.

Path Tracing and MLT were implemented to render the church reconstruction. Path Tracing is an unbiased stochastic rendering algorithm which numerically solves the rendering equation. Rays starting at the eye are traced through the scene in order to create a path from the eye to a light source, and the contribution of these paths forms an image on the camera. MLT is an extension to Path Tracing based on the Metropolis-Hastings method from computational physics. Previous path information is used to guide the current path (via mutations to the previous path) in order to more efficiently explore path space. These new paths are probabilistically used as the basis for further paths via carefully chosen statistics. Finally, for comparison Mental Ray; a rendering package that already exists within Maya for realistic rendering of synthetic scenes was also used. Commercial renderers allows users to specify rendering and lighting properties for an image for ease-of-use through graphical user interfaces. It was decided however to implement the two rendering algorithms to have full control and overview of the rendering application.

Matte materials were approximated as diffuse BRDFs. All glossy and specular materials such as the gold painted icons and tile floor have been approximated using a Ward BRDF [War92].

7. Results and Discussion

A collection of rendered images of the interior and exterior of the church are shown in Figure 10. These images illustrate the level of fidelity that is obtainable through unbiased rendering methods. Such methods present great opportunities that have not yet been fully explored in the cultural heritage reconstruction domain.

This virtual reconstruction is an example that shows how environments that are mostly indirectly lit (in this case dark environments) demand a significant amount of computational power to converge to a satisfactory image. Accelerating rendering for interior scenes predominantly lit by indirect sunlight is currently a difficult problem in unbiased rendering algorithms such as Path Tracing. As a consequence, it takes several interreflection computations before the light is traced back to the light source. This increases rendering time to the overall image substantially.

HDR environment maps have a dense data set that do not need any interpolation. Problems often arise however, during the sampling stage while rendering interior environments. Importance sampling for instance tend to favour areas of the greatest luminance values (such as the sun). This is generally appropriate for rendering objects using interior HDR environment maps, or use of synthetic light sources inside a scene. However, most paths in unbiased rendering methods will struggle to reach the exterior light sources via narrow entrances such as windows and doors.

Figure 9: *Top: Comparison of the doorway. Bottom: Two Path Traced images combined into one. Top half: 200 samples per pixel. Bottom half: 16,000 samples per pixel.*

Grainy noise will therefore remain present until the image appears converged. Figure 9 illustrates the visual impact of this noise. In this case, it was necessary to leave the scene to render several hours on a cluster of computer nodes to accumulate more than 16,000 samples per pixel. When rendering synthetic objects mostly lit by direct illumination however, images converge significantly faster, this is clearly visible in the exterior renders of the church. After 2,000 samples per pixel the exterior images appears fully converged. In an effort to reduce or altogether remove noise in rendered images, it is also possible to employ noise reduction filtering as a post-process. However, for the purpose of this paper, none of the presented images have gone through a filtering process.

The approach of using a nearest-neighbour inspired HDR environment map is an attempt at a more uniform distribution of light for a scene. Traditional HDR environment maps also contain incident illumination conditions for a particular point in space. This interpolated approach however, uses incident light captured at key locations (doors and windows) of the church. While this method is not fully physically correct, it generates a simple, easy-to-implement approximation of a skydome to be obtained from relatively few measurements. The approach can complement traditional use of image-based lighting, especially in cases where a lack of roof-access or open spaces prevent capturing of ideal skydome HDR environment maps. Collecting larger data sets would increase precision of the generated skydome.

8. Conclusion and Future Work

In this paper we have investigated the use of HDR IBL lighting for a cultural heritage site; the Panagia Angeloktisti, a Byzantine Church in Cyprus at various times of the day. The full reconstruction pipeline was detailed, and approaches to render interior low lit environments were presented. Unbiased rendering algorithms deliver photorealistic and accurate images, despite this, these approaches are rarely used in the cultural heritage domain due to long computation times and are not easily implemented.

A method to generate HDR environment maps from interpolated spectrophotometer data was also presented. While the method discussed in this paper is not physically correct, it presents an alternative approach based on interpolating real world RGB values. Future work may investigate other interpolating approaches to improve the accuracy of the model.

Modelling physically accurate gold for cultural heritage items is a difficult task due to the level of complexity often found in old or deteriorated items. A more accurate representation of the reflectance properties of the gold is a subject for future work.

The current model is a representation of the church as it stands today. While it is not possible to verify the light captured today valid for what it would have been in the past, future work will consider how the site and its lighting may have changed through the ages and investigate the changes of light scattering due to pollution, positioning of the sun and climate changes at various periods in time.

Acknowledgements

Figure 5 and interior images in Figure 10 were tone mapped using the method presented by Drago et al. [DMAC03]. We would like to thank the Cypriot Department of Antiquities for giving us permission to collect data at the church, Ioannis Eliades of the Byzantine Museum and Art Gallery, Yiorgos Chrysanthou from the University of Cyprus for input, Andreas Foulias for his help on information regarding the church, and Eva Zányi, Mark Mudge, Carla Schroer for their valuable help. Also, many thanks go to the caretakers of the church for their assistance.

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Figure 10: *Various interior and exterior renders of the church. Left images (top-down order): 1) Path Tracing with HDR Env. Map (12:00), 2) MLT with with HDR Env. Map (12:00), 3) Interior render using Path Tracing with spectrophotometer data HDR Env. Map (12:00). 4) Exterior render using Path Tracing with spectrophotometer data HDR Env. Map (12:00). Right images: Path Tracing at 1) Sunrise, 2) Mid-day and 3) Sunset. 4) Physical sky render in Mental Ray.*