

Cultural Heritage Predictive Rendering

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Abstract

High-fidelity rendering can be used to investigate Cultural Heritage (CH) sites in a scientifically rigorous manner. However, a high degree of realism in the reconstruction of a CH site can be misleading insofar as it can be seen to imply a high degree of certainty about the displayed scene - which is frequently not the case, especially when investigating the past. So far, little effort has gone into adapting and formalising a Predictive Rendering pipeline for CH research applications. In this paper, we first discuss the goals and the workflow of CH reconstructions in general, as well as those of traditional Predictive Rendering. Based on this, we propose a research framework for CH research, which we refer to as “Cultural Heritage Predictive Rendering” (CHPR). This is an extension to Predictive Rendering which introduces a temporal component and addresses uncertainty that is important for the scene’s historical interpretation. To demonstrate these concepts, two preliminary case studies are detailed.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism, I.3.8 [Computer Graphics]: Applications

1. Introduction

High-fidelity rendering allows for the investigation of Cultural Heritage (CH) using physically based methods. The *Predictive Rendering* pipeline [GTS*97], presented the key principles to render and validate real-world scenes. In juxtaposing the image synthesis pipeline for modern scenes with historical sites however, it becomes apparent that in its current state, it only satisfies renditions of sites as they stand today. For historical representations, we must identify and add appropriate, accurate scene metadata, including its temporal components. Scene metadata here refer to information that is meaningful in its interpretation for the historical expert observer. This includes scene setup (geometry, materials and illumination) based on how people and natural forces interact with the site; incorporating both physically and historically-based properties to deliver plausible images.

We propose a novel research framework to reverse-engineer past sites by extending Predictive Rendering to make use of extant objects and records, experimental data and expert opinion. Through *Cultural Heritage Predictive Rendering* (CHPR), the aim is to investigate and understand the motivation, function and visual perception of CH sites in the present and past. Two case studies have aided in its

development: Panagia Angeloktisti, a Byzantine church on Cyprus and the Red Monastery, a Coptic site in Egypt.

1.1. Problems in Recreating the Past

Efforts are being made to standardise methods for virtual CH research [Gro96, DCM95, 3dC09, AG07, DH09, GB11]. However, achieving reliable rendering results for CH research remains a demanding challenge for several reasons, including:

1. Few rendering standards have been established and widely-adopted specifically for CH rendition.
2. Validation of the past: physical condition and access to historical records can lead to much interpretation.
3. Sensitivity-of-CH concerns regarding data collection.
4. Current hardware and software limitations.

There are currently no universally accepted standards to assess accuracy of CH renditions. Metrics that partially contribute to documentation and validation are borrowed from other sciences and disciplines. Examples include (but are not limited to); Spectroradiometry, Laser Scanning [BR02], Ground Penetrating Radar (GPR) [CL10] and Reflectance Transformation Imaging (RTI) [MGW01, FBM*06].

2. Background

2.1. Motivations for CHPR

Hypotheses about the past can be simulated to provide a research context in which a virtual rendition closely resembles its (known) physical counterpart. Currently, no general framework for this exists, despite many high-fidelity case-study reconstructions have been published in the last 20+ years [HMD*10]. Nevertheless, several standards exist related to documentation and data management of CH. The CIDOC Conceptual Reference Model [Gro96], Dublin Core [DCM95], Functional Requirements for Bibliographic Records (FRBR) [IFL09], London Charter [DH09] and the Sevilla Charter [GB11] some examples. CHPR aims not to replace or compete with them, as it is not a framework for data management or documentation purposes. Principles from one or more existing standards can be used within a CHPR context. Our framework simply combines efforts discussed in prior CH graphics publications to fall under a single pipeline promoting standardisation, measurability (where possible) and reproducibility. The choice of documentation and data management methodology, should be up to the researchers responsible for the reconstruction.

Several publications have discussed the taxonomy of CH renditions to best fit with the current workflow of historical experts. Foni et al. [FPMT10] for instance, proposed a broad classification system to several approaches of visualising CH objects. The taxonomy does not distinguish between various high-fidelity offline methods, which limits its use to describe output differences for a number of physically based algorithms. The DECHO framework [ABV11] is a pipeline for data acquisition, management and visualisation of CH objects as they stand today. Our framework emphasises delivering both physical and historical accuracy of the past.

2.2. Visualising and Assessing Time and Uncertainty

Visualising time and scene metadata relevant to various time periods (including uncertainty) is an unsolved problem. Most publications addressing this topic today suggest displaying objects with lower confidence in less photorealistic graphics [RD03, ZCG05, SJW*06, SJM*10]. Several of these papers argue that the highlighting of scene metadata through Non-Photorealistic Rendering (NPR) approaches show where more research needs to be done in order to minimise ambiguity for the viewer. Zuk et al. [ZCG05] suggest displaying temporal uncertainty in 3D models through approximate time windows, and by introducing uncertainty visual cues by rising and lowering of objects, wireframe and transparency. A real-time 4D VR approach was implemented by Laycock et al. [LLDD08]. Both papers suggest a static representation of objects that swap models based on user input determining time periods, and favour blending of time periods using a slide bar representing time.

2.3. Assessing a Reconstruction

Currently, the assessment of CH reconstructions remains an ad hoc process, mostly without quantifiable means; making reproducibility of any reconstruction limited. Few universally accepted standards, and practical issues in sharing 3D models make this a recurring problem [KFH09]. Niccolucci and Hermon [NH04] proposed a fuzzy logic approach to assess possible scenarios by numerical calculating an index of reliability, allowing for greater measurability and verifiability. Plecinckx [Ple08] proposed a number of methodologies to develop sustainable visualisations of the past through *Interpretation Management* to structure and rationalise the interpretation process; including source assessment, source correlation and hypothesis trees.

2.4. Existing Predictive Rendering Framework

Rendering aimed at photorealism can be broadly divided into two main categories; Believable and Predictive [Wil08]. Many rendering pipelines that deliver photorealistic images, including offline approaches, fall into the former category. Predictive Rendering concerns generating images that are both perceptually and physically correct. Its foundation is divided into three main sections [GTS*97]: 1) Goniometric (validation of surface properties), 2) Radiometric (accurate light transport simulation) and 3) Perceptual (correct output of final image to the human eye). For present day CH documentation, this framework alone provides a satisfactory pipeline to generate such results.

3. CHPR: An Overview

CHPR extends Predictive Rendering with an experimental archaeology approach to generate plausible renditions of the past. A fourth comparison section is introduced to deal with the *Historical Comparison*, see Figure 1. This section assesses historical accuracy relevant for historical experts, allowing for scene metadata to become a priority.

The rectangles represent measurement comparisons. Scene metadata is important for a site's visual appearance, and needs to be quantified. Examples include: sun position, how sunlight enters the site (e.g. coloured glass), objects that occlude areas and how they affect amount of light present, surface properties, and finally, attributes of indoor illumination. This is further detailed in section 5.

The square shows underlying research to process and quantify historical content in the pipeline and display these correctly. All historical records available (literary texts, extant objects and architecture, and images such as photographs or paintings) must be examined. Their uses must be assessed by qualified experts to aid in their interpretation.

The large arrows show that once scene metadata has been added, it can be displayed to the end observer as a plausible representation of the past. Unlike the previous three sections

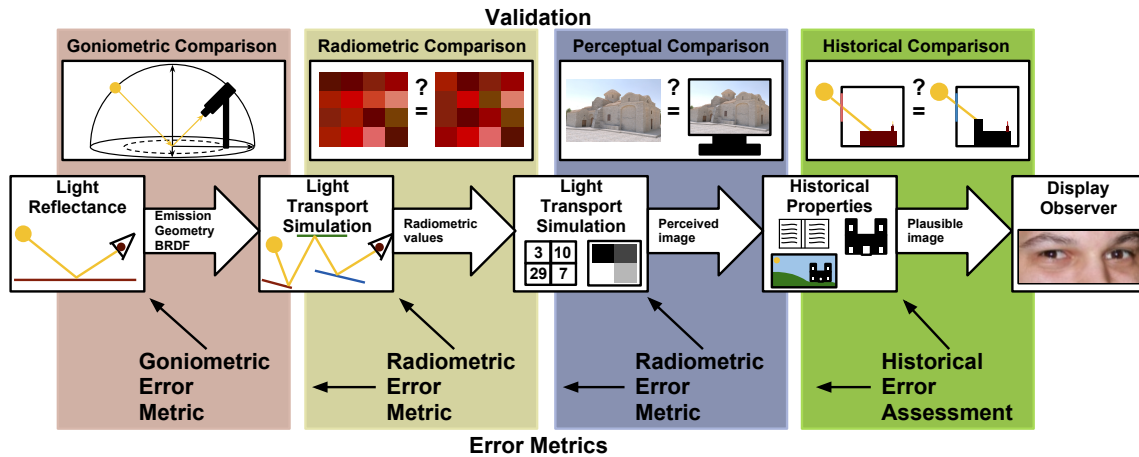


Figure 1: The framework is an extension of the existing pipeline [GTS*97]. A fourth section considers the accuracy of the historical data for the virtual scene. This “scene metadata” holds information about geometry, materials and light sources relevant for its historical interpretation.

however, an error metric (small arrows) cannot be objectively produced from the comparison of historical records. Each rendition must be re-assessed based on new input from historical experts and then added to new iterations of assessment until plausible images have been obtained. The feedback loop nature of the pipeline allows researchers to improve upon the previous sections where necessary.

Unlike traditional Predictive Rendering, CHPR’s aim is not only at producing results indistinguishable from the photorealistic ground truth. Instead, its aim is also to answer questions relevant in CH research; particularly those that pertain to the relationship between appearance and function of a site. This is done by obtaining a number of plausible physically and historically-based renditions to obtain new knowledge or confirm previous assumptions about the past.

3.1. Historical Comparison

The Historical Comparison deals with the validation of the virtual scene as viewed by the historical expert. The lack of quantifiable data to compare with (e.g. photographs) makes objective assessment of most reconstructions a recurring problem. Through cross-disciplinary collaboration, sufficient evidence (based on input available today) must be gathered to generate renditions of the past that have scientific merit.

Once these inputs have been heuristically and experimentally determined, they can be added to or corrected for in the virtual scene. To minimise error, the establishment of a timeline (starting from the site as it stands today and going backwards) make it possible to compare a site at its different stages in history. Previous work mentioned in Section 2 suggest that timelines consisting of time windows efficiently convey how sites may have changed over time. CHPR adopts a similar approach, see Figure 3.

Unlike traditional Predictive Rendering, there will not be a single correct solution, rather several *Timeframes* and *Scenarios* need to be produced for a timeline. A Timeframe is a virtual representation of a real scene in a time window (similar to Zuk et al. [ZCG05]). However, as each of these can span several years, so can the visual perception within it in each period. It can therefore consist of several Scenarios. Most scene metadata between sibling Scenarios will remain largely the same. However, a Scenario can add minor changes; particularly how lighting affects the perception of a site. Different time of day or event may alter its appearance significantly, despite there not having been made any geometric or material changes. An example of a Scenario can be a sermon inside a religious building, while another can be the perception of the scene at some other time.

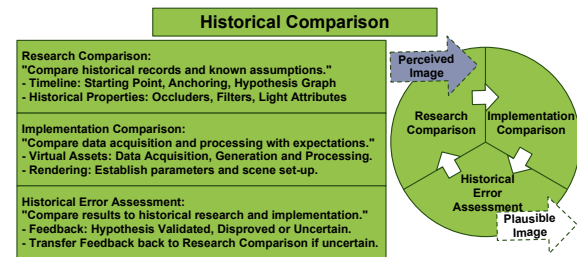


Figure 2: Historical Comparison consists of three main steps: Research Comparison, Implementation Comparison and Historical Error Assessment. The cycle repeats until a plausible image is generated, to then determine confidence of a historical hypothesis.

For each Timeframe, a cycle of three steps are important to assess in order to achieve plausible output, see Figure 2. The *Research Comparison* (elaborated in sections 4 and 5) deals with the establishment of scene metadata for each

Timeframe and Scenario. Historical experts can both compare and convey expectations or known assumptions based on input data available today to develop and update the timeline. The present day should be the starting point where possible, to then step backwards in time to the prior major alteration of the site in order to minimise error.

Implementation Comparison (see Section 6) allows for the data acquisition and processing (technological resources) available to be compared against assumptions and expectations established in the previous step based on the needs of the reconstruction. Methods and approaches are either added or removed from the virtual scene before rendering based on their relevance for the scene's (historical) interpretation.

Once an image is synthesised, the output needs to be evaluated in the *Historical Error Assessment*, see Section 7. If results are deemed implausible by the historical experts, another round of the comparison cycle is needed, starting at the Research Comparison again with new knowledge from the last step. Any physical simulation problem must be corrected for in the prior three sections (e.g. incorrect BRDFs or texture maps). Once the image is deemed plausible however, it can be validated with greater confidence or rejected as a result of CHPR.

Best available tools and techniques should be used to capture, process and display scenes. Resources for CH projects may be limited, preventing this. It is thus important to document all decisions taken before and during a reconstruction (e.g. using one of the existing standards), as well as overview all limitations, to promote reproducibility. These notes should be made throughout the whole Historical Comparison, should any data be lost or needed again in the future.

4. Research Comparison: Developing the Timeline

During Research Comparison, information regarding historical resources and existing knowledge are compared to best determine starting point. If the site no longer exists, the most recent and accurate photographs, archaeological drawings, similar archetypes (*"The original pattern or model from which copies are made; a prototype"* [Oxf]) or other records and expert opinion can be used to form the starting point.

4.1. Starting Points

Generally speaking, four existing conditions can act as a starting point:

- The site no longer exists, and:
 - 1) - is entirely replaced by a modern site.
 - 2) - is mostly gone; only a few objects occupy the area.
- The site exists, and:
 - 3) - is extensively damaged.
 - 4) - is in relatively good condition.

The condition of a site determines how much data needs to be gathered through experimental archaeology, and what

can be extrapolated from existing resources, including similar sites. However, availability of; a) historical resources, b) data capturing tools and c) size, time, knowledge and efficiency of team working on the project are also important factors that make up quality of output results.

4.2. Anchoring Timeframes

Once a starting point has been established, a timeline can be developed. By starting at (closest to) the present day, here denoted by T_0 , it is possible to create the first iteration of the scene. This acts as a primary anchor (root node) from which all subsequent Timeframes will be based on. If T_0 exists today, it can be validated to the real scene using traditional Predictive Rendering, see Figure 3.

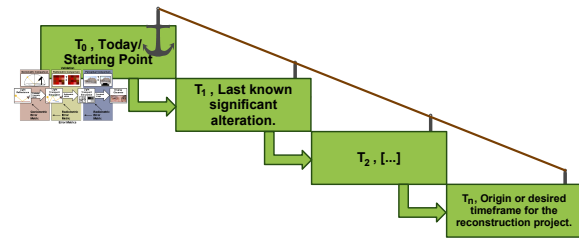


Figure 3: Once the primary anchor is set, T_0 , it is possible to determine the last significant alteration, enabling an iterative approach to investigate the past. Each Timeframe requires the three comparison steps to ensure a reconstruction remains plausible.

After thorough investigation of the starting Timeframe, a fundamental understanding of the environment, space and lighting is obtained. It is then possible to go to T_1 ; the last known significant alteration of the site, and from there; the subsequent Timeframes. This is done iteratively until T_n (origin or desired point in time) is reached.

All subsequent anchors are based on their ancestor Timeframes in successive order, and therefore also the primary anchor; making T_0 the most important parent. By having a child Timeframe (further back in time) inherit information from its parent allows for children renditions to preserve information across the entire timeline, ensuring that any errors that occur will at least remain consistent throughout all Timeframes, and can be corrected for accordingly in a more straightforward, systematic manner. This also allows for reuse of assets and resources where appropriate, and decreases time spent altering the scene between Timeframes.

Part of the research problem in CHPR is the attempt to develop a logical chain of events starting from the objects' modern day state. Timelines may break into several possible pasts if several hypotheses are assumed to be valid. In such instances, a Hypothesis Tree/Graph [Ple08] is useful to represent the timeline.

5. Research Comparison: Historical Properties

Historical Properties are the scene metadata describing the virtual scene (and its parameters) for a Timeframe. Determining this information allows researchers to investigate how geometry, materials and illumination alter the visual perception of a site at each Timeframe and Scenario. These properties do not have an impact on the rules of physically based simulation, but address how human and natural forces have affected the scene. The Research Comparison at each Timeframe involves investigation of all Historical Properties that make up the virtual scene, see Figure 4.

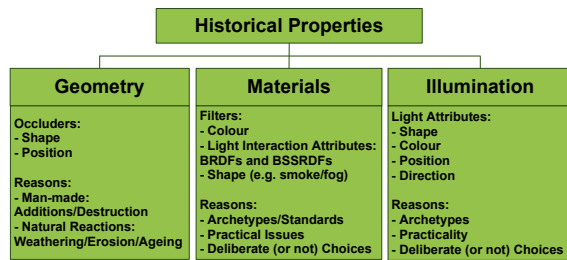


Figure 4: Historical Properties determines the appearance of geometry, materials and light for a Timeframe. Geometric changes (occluders) may affect how much light enters a scene. Material changes affect (filters) light reflectance. Light attributes describe scene metadata about how the physical components of the light source have been used by human beings.

Differentiating between physical and historical data can be difficult if the same terminology is used, and may lead to needlessly verbose descriptions. As Timeframes only store changes from their parents, these alterations can be regarded as additions or subtractions to the scene (similar to version control systems). For the purpose of simplicity; Historical Properties refer to geometric, material and lighting changes as *occluders*, *filters* and *light attributes* respectively. Occluders (e.g. pillars, walls) block light entirely (or partially) from propagating in the scene, with the addition or removal of filters (e.g. coloured glass, encaustics, mirrors) providing a high-level description of scene materials. Light attributes describe light sources (e.g. ingredients to oil lamp light) and their uses in Scenarios and Timeframes. Figure 5 shows examples of how Historical Properties can affect a scene.

5.1. Occluders and Filters

Existing or removed geometry have features such as shape and position. By identifying them, it is possible to investigate how objects have blocked light, or allowed light to enter, and their purposes in relation to its parent and child Timeframe. Examples of this include neighbouring buildings, large columns, filling/removal of walls, or addition/removal of objects. If their positioning has changed drastically, the amount of overall lighting will also differ.

Filters provide high-level contextual information on how materials have been added to a scene, including; changes in surface textures and BRDFs/BSSRDFs properties to describe surface light reflection. Figure 6 shows photographic examples of how wall painting surfaces can change over time. Participating media or subsurface scattering volumes (including their shapes) are other examples of filters, and become important when simulating smoke or fog. For particular cases, it may be beneficial to classify the scene camera as a filter with zoom, lens, unsharp, colourisation, particularly if there is an actual camera involved.



Figure 6: Art inside the Red Monastery. 6(a) and 6(b) show differences in wall paintings covered in soot and after conservation. 6(c) was affected by an earthquake. 6(d) shows paint corrosion and external influences that have chipped off parts of the painting.

5.2. Rendering and Illumination

Computing accurate lighting is key to deliver correct renditions and minimise interpretation errors. Physically based algorithms today deliver highest possible accuracy of light transport simulation available. Unbiased approaches (e.g. point sampling methods) may have a slight advantage in this regard as it is better to remain unbiased, than to potentially introduce algorithm-specific artefacts (other than variance).

Unbiased images still take a long time to synthesise. Fast communication between historical experts and graphics researchers is important, particularly in the early days of a reconstruction project. In the first cycles of the Historical Comparison it may thus be useful to consider physically based believable rendering in order to use a coarse representation of the scene before refining output to develop plausible renditions of the past. Once an initial establishment of the Historical Properties have been set, offline rendering methods (such as unbiased algorithms), can be used to improve the representation of the scene. At this point accuracy plays a much larger role. Recently, approaches tailored for CH renditions have also been introduced; including *Image-based Shooting* [HBRDC11] and a system extending *Surface Depth Hallucination* [MGWH11].

RTI [MGW01, FBM*06] considers image space, but is useful in the Research and Implementation Comparisons by providing a better understanding of CH objects. Interactive, unnatural lighting conditions such as specular enhancements and diffuse gain can provide information that is otherwise invisible to the human eye.

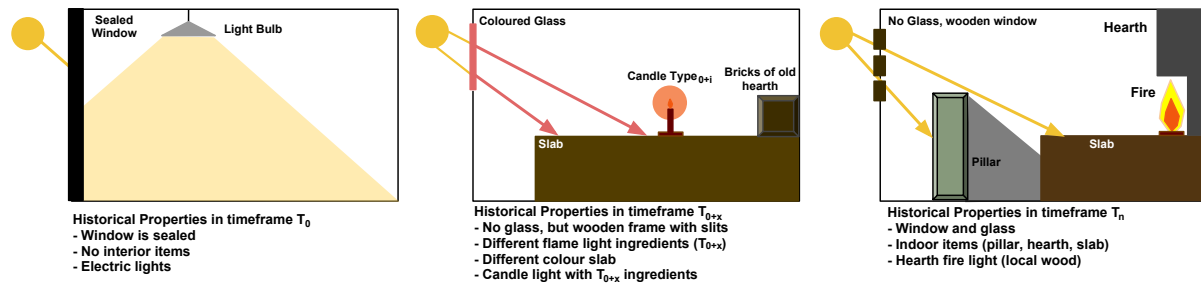


Figure 5: Historical Properties give meaningful, high-level description of a scene for its historical interpretation. Examples include the existence of glass (and type of glass/window) will affect sunlight in the scene. Interior objects can partially or fully occlude light sources. Surface colour and light reflectance of objects change greatly over time due to both natural weathering and human influences. The example shows T_0 , T_x (a Timeframe before the origin of the site) and T_n (site origin).

5.3. Light Attributes

Light Attributes refer to the high-level description of illumination based on historical records, expert opinion and experimental data. These parameters are important in order to fully understand how the scene was observed, and how to apply them in a virtual setting. Generally speaking, light sources can be defined as having: shape, position, direction and colour. Unlike Occluders and Filters, Light Attributes can alter the visual perception of a scene with considerably less real-world effort between Scenarios. For instance, a simple change of direction or translation of a light source can have a significant impact on a site's interpretation. Not only will the ingredients to artificial light be important, but its use and influence on the scene must be described for each Timeframe and Scenarios. Light Attributes can be split into two main categories: Skylight and Artificial Light.

5.3.1. Skylight Modelling

Sunlight has a major visual impact; from directly lit areas to sections in deep shadow. Scene illumination changes substantially at different times of the day, as shown in Figure 7. Accurate simulation of the sky is computationally expensive as all elements need to be addressed during rendering. Simulating light transport in the sky [PSS99, JDS*01] can serve to recreate sky conditions of earlier times, when the air was much clearer than now. Including sky elements and star constellations if these are important for the simulation. High Dynamic Range (HDR) imaging captures lighting taken at physical locations and can be used to virtually recreate natural lighting conditions at CH sites today [DTG*04, HAD*09].

5.3.2. Artificial Light Modelling

Artificial light can be split into two main categories: Flame and Electrical. Their physical simulation differ greatly, but their uses break down to being either for deliberate or practical applications. Deliberate use of light attempts to convey a particular visual perception of a scene to the end observer.

Practical use distributes as much lighting as possible in the surrounding for visibility purposes. Careful attention must be made to how the lights were prepared, used and maintained to determine how to add appropriate light sources to the scene at various Timeframes.

6. Implementation Comparison

The Implementation Comparison deals with evaluating acquired data and its subsequent processing to the expectations that are established in the Research step, before rendering commences. The suitability of employed technologies and methodologies for the end result are determined based on the needs of the historical experts. This includes for instance; empirically or experimentally acquired data, and virtually generated or processed data. This multi-disciplinary cross-checking enables for any potential misinterpretations and miscommunications to be dealt with before rendering.

6.1. Data Acquisition

All raw data captured needs to be relevant for its interpretation; including acquisition and generation of geometry, materials and light sources, based on the Historical Properties. The acquisition of accurate experimental data is essential to develop quantifiable results for a CHPR pipeline.

The starting point determined in the Research Comparison dictate the technologies needed for data collection. Subsequent accuracy is then affected by the capabilities of the technologies used. This is especially the case if the raw data is acquired experimentally, rather than generated through human interpretation. Comparison of raw data with a historical expert may not be essential for all cases if T_0 is the present day. Nevertheless, adding historical expert interpretation becomes increasingly important the further back in time T_x is.

Point cloud acquisition from laser scanning provides highest precision for T_0 where the site still exists. Recreating objects through experimental archaeology techniques

can build a library of physically objects (from human interpretation) that can be laser scanned as well; Rome Reborn 1.0 [FAG*08] is an example of this. Procedural content and manual 3D modelling also allow for content acquisition through content generation. These data sets should be based on archetypes, archived maps and textual records.

Furthermore, the use of spectroradiometry, for instance, will aid in collecting information about lighting. Data should be based on historical records and gathered methodically, dictated by the resources available and expert opinion. In order to recreate a past flame for example, it is necessary to understand its key components [GMMC09], such as:

1. Ingredients: E.g. Fuel, Additives and Wick.
2. Flame containers: E.g. Luminaires, Torches and Hearths.
3. Surrounding environment: Components of the air.

Surface colour at CH sites may be in a weathered state. While cutting a piece of a material from a sensitive site is never an option to obtain data on site, it is often possible to determine the *as new* appearance of raw materials (such as stone) with a high degree of certainty, even after millennia of weathering by cutting out nearby similar types of material from a non-sensitive site, and use this for measurement. In most cases, this should deliver satisfactory results for the question under discussion.

6.2. Data Processing

Comparing Data Processing methods addresses how raw data is processed in order to deliver minimal error before image synthesis, based on technologies available. This includes deciding hardware tools, rendering parameters, mesh processing algorithms, surface colour estimations; i.e., the implementation of the Historical Properties.

Physically based image synthesis algorithms have method-specific parameters that determine the final output. In a Path Tracing renderer; termination conditions (samples per pixel, time restrictions, maximum ray depth) and image processing (filtering) images all have an impact on the final image. During rendering, a comprehensive description of all rendering parameters should be listed in order to provide detailed and reproducible results. The appropriateness of HDR and tone mapping should also be established, particularly as careless use will lead to incorrect interpretation of the scene with regards to colour and luminance.

Inaccuracies from simplifying Level-of-Detail (LOD) of 3D models can also affect the visual perception of the scene as light is now reflecting off a less detailed model. The weathered state of CH today may increase the need for texture map restoration. Textures are difficult to reconstruct as there is no means to validate whether the estimation is correct. Approximations based on existing archetypes is possible, and non-figural art may be more straightforward in this regard. Geometric patterns can often be interpolated and still convey most of the same information to the end observer.

Figural art on the other hand have artist-specific, local and regional characteristics [Cur00,Ris01], which are important for their correct interpretation, and may therefore be more difficult to reverse-engineer based on empirical data sets.

7. Historical Error Assessment

The Historical Error Assessment compares output images with the expected results from both the Research and Implementation Comparison steps. Historical experts can determine how close to the assumptions the scene rendition is and either: confirm plausibility of the synthesised image, or declare the image as implausible. If the image is deemed plausible, this allows historical experts to confirm or reject previous hypotheses/assumptions with greater confidence. On the other hand, if the image is deemed implausible, this can be due to incorrect Physical Comparison (Goniometric, Radiometric or Perceptual) or incorrect Historical Comparison (Research or Implementation).

7.1. Incorrect Physical Comparison

Incorrect physical representation of the scene results in incorrect output. Currently, materials in CH reconstruction are often approximated as diffuse or based on analytical BRDF models that are heuristically applied to the scene (e.g. Phong, Ward, Lafortune). These results tend to be believable, but not physically correct to the real scene. This can be fixed by measurement, however, sensitivity of CH often prevent this, resulting in slower establishment of predictive results.

If results dictate that underlying physical simulation is the reason for incorrect interpretation, the prior three sections must be reconsidered. All sections can be re-evaluated because of the feedback loop nature of the framework. For instance, in cases where scenes with high contrast between light and dark areas exist; not having HDR displays to deal with these ranges of light means that tone mapping can be employed. However, tone mapping artefacts may affect the interpretation of the scene. The historical experts should therefore be exposed to a variety of approaches to displaying HDR content, including viewing images at a variety of single exposures.

7.2. Incorrect Historical Comparison

Implausible images should be corrected for by establishing feedback from both historical and graphics experts to determine where the rendition may have gone wrong. It is important to keep both an open and critical dialogue to understand when output are implausible, and when a rendered image is in fact plausible (from both a simulation and assumption standpoint), but needs to be rejected as a probable Scenario. Each time new information from both plausible and implausible results transpire, the timeline must be updated accordingly for the next round in the section's cycle, or to move on to the child Timeframe.

7.3. Assessment Concerns

Another concern in this step is that historical experts completely new to computer graphics may incorrectly assess photorealistic images. Conveying the difference between historical and physical simulation accuracy is a key distinction to make when collaborating. People unfamiliar with high-fidelity rendering (including its limitations) may in some cases overlook aspects of the scene. It is therefore important during assessment that historical experts new to photorealistic image synthesis be thoroughly exposed to a variety of rendered solutions in order to provide better judgement of the final image.

At the moment, the Historical Comparison will be subject to expertise, hardware and resources available during each cycle step. Each reconstruction project will set different demands to achieve predictive results. It is therefore important to consider how external factors can influence output. Subjective assessment cannot be avoided, but should be minimised where possible. The evaluation can be as simple as an informal dialogue between experts. Ideally however, some statistical data should be generated and analysed; either through appropriate psychophysical experiments or surveys to determine plausibility of a rendered scene. Available of historical expertise for a particular site may in some instances prevent this.

8. Case Examples

Traditional Predictive Rendering is still not a fully solved problem. This is because not all real-world phenomena have been simulated in a physically based rendering context. CH projects aiming for predictive results are subject to the same and additional obstacles because the temporal domain is also considered, and not all information will be available. Both Panagia Angeloktisti [HAD*09] and The Red Monastery [Bo104, HBRDC11] were modelled using industry standard 3D modelling software. The latter project was built on 2D CAD drawings developed by architectural historians on site enabling faster modelling times.

Both models were created before the complete formulation of CHPR, and contributed to its development. The case examples highlight where results gave clearly visible differences, and what has been done to combat inaccurate believable images. This is done instead of repeating how the models have been refitted to the CHPR pipeline. The iterative nature of CHPR encourages improvement through feedback, and allows limitations to be improved upon.

There are two primary motivations for the reconstructions of Panagia Angeloktisti and the Red Monastery: 1) to widen the site's understanding through high-fidelity renditions, particularly as both buildings have changed their appearance since they were first built, and 2) to document the sites as they stand today, should anything happen to them.

8.1. Panagia Angeloktisti

Panagia Angeloktisti's origin can be traced back to the sixth century (T_6), erected on the ruins of a three-ailed, wooden roofed early Christian basilica [Fou04], similar to the first churches in Cyprus [Ste10]. Its modern day appearance however, pertains largely from its twelfth century iteration (T_5). It has undergone many changes throughout history, most noticeably today are: 1) A vaulted chapel from the twelfth century added on the north side of the church (now also containing wall-paintings from the fifteenth and sixteenth century). 2) A Latin (Gothic) chapel added in 1302 on the south side of the church (T_4). 3) Throughout the church's history a variety of wall paintings and icons have been added and removed within its space (T_3). 4) The removal of wall segments in the northern section, including a small tower (T_2). 5) A modern Gothic-inspired bell tower that was added in the early 1900s (T_1) only to be removed in 1955 as it was deemed inappropriate based on the history of the rest of the building, by the Antiquities Department of Cyprus. The interior has undergone a variety of changes related to additions of paintings and the placement of interior objects [Fou04, BYK07]. Most noticeably today is the fading and damage to the interior art and the addition of a modern floor and chairs that largely occupy the church space.

A Hypothesis Graph (constructed as a tree of nodes/Timeframes) was used in the Historical Comparison to assemble the timeline based on information from local experts, texts and local caretakers (summarised condensely above). The primary anchor is the modern day representation, from which the texture maps were acquired and added for the Implementation step. As the church is still used today, it was decided to use the non-invasive approach of 3D modelling and site photography. Over 10,000 photographs were taken.

The visual impact of a site changes dramatically over the span of a day. Figure 7 shows the use of IBL captured close to the real-world physical location at several times of the day (sunset 05:30, 12:00 and sunset 20:30).

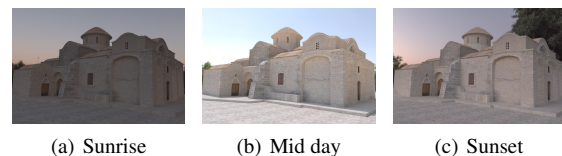


Figure 7: The modern day Panagia Angeloktisti rendered at various times of the day using locally acquired IBL.

Figure 8 shows the church at T_1 (1955) and T_2 (1859) respectively. Panagia Angeloktisti has not been discussed at great lengths in art history or archaeology literature, however, it is possible to draw similarities between Panagia Angeloktisti and other churches on Cyprus such as Panagia Chrysiotissa and Panagia Afentrika [Ste10].

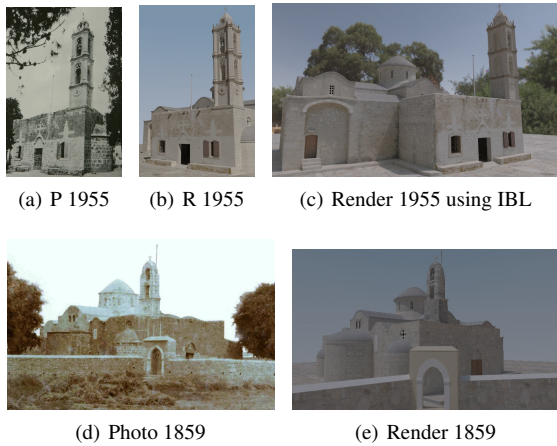


Figure 8: Panagia Angeloktisti at the various T_x . Top Left: Old archive photo from 1955 (T_1) Images courtesy of A. Foulis [Fou04]. Top Middle and Right Rendering of 1955. Bottom Left: 1859 T_2 ; earliest photograph known of the site, courtesy of L. Bonato et al. [BYK07]. Bottom Right: Rendering of 1859.

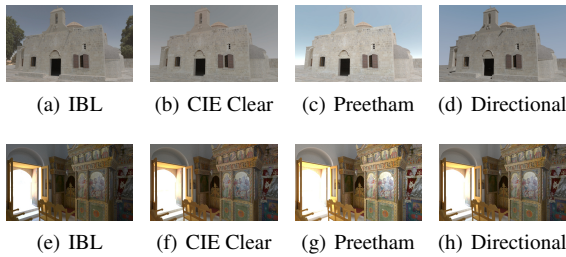


Figure 9: Sky model examples of Panagia Angeloktisti, 12:00, 18th June 2008. Top: Outside the southern entrance. Bottom: Inside, facing the northern entrance. Each image was rendered for 10 hours on a 24 node quad core cluster.

8.1.1. Other Considerations

Figure 9 shows that simply adding different sky models will affect exterior and interior perception. Each of the renditions are relit at the same time of day and year using different sky models including IBL, the CIE Clear Sky model, Preetham and a directional light source with a background colour based on sky values from the IBL environment map.

HDR documentation and reproduction becomes a necessity for scenes with significant dynamic range. As HDR displays are not readily available, tone mapping becomes important to consider. However, as no Tone Mapping Operator (TMO) can perfectly map all features of images for all cases. Figure 10 illustrates output from several popular TMOs [MKMS07]. The output of these images are of varying visual quality which may in turn affect its interpretation. To date, no publication investigate TMOs based on the needs of historical experts.

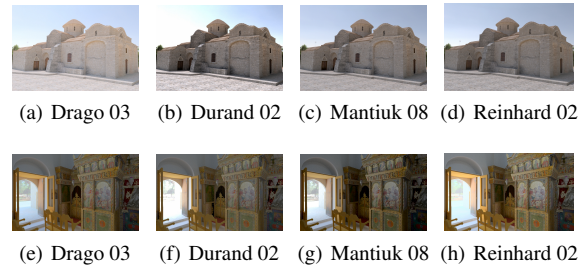


Figure 10: Panagia Angeloktisti mid day (interior and exterior) with various Tone Mapping Operators.

During investigation of the church interior, local caretakers and historical experts argued that the perception of the mosaic depends significantly on time of day. The considerable change of visuals dependent on different lighting conditions inside the Panagia Angeloktisti apse was supposed to change its visual appearance dependent on exterior lighting.

Further investigation using RTI suggest that increasing the LOD for the mosaic (and modelling its individual tesseraes) is essential for its accurate representation. Figure 11 shows use of RTI relighting to investigate its visual perception. The difference between simple texture map relighting and RTI. When the RTI is compared to a relit texture map, clear distinctions between each tesserae can be seen [ZSMA07]. As expected, it is observed that changes in light mainly affect specular materials. Areas of gold and metallic surfaces changed the most when the lighting changes. In the texture map, the scene is uniformly lit over the surface; significant perceptual cues about the scene are lost as highlighted in the Visible Difference Predictor (VDP) [Dal93] comparison.

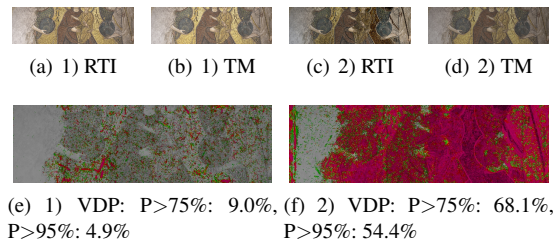


Figure 11: RTI of the Panagia Angeloktisti apse. When the RTI is compared to a relit Texture Map (TM), clear distinctions between each tesserae can be seen in the mosaic. In the TM, the scene is uniformly lit over the surface; significant perceptual cues about the scene are lost as highlighted in the VDP comparison.

8.2. The Red Monastery

The Red Monastery model is still an ongoing project. A preliminary Hypothesis Graph was created in the Historical Comparison to create the timeline based on input from

experts and existing publications. The modern monastery acts as the primary anchor, from which texture maps and 2D CAD files were used in the Research Comparison step. However, unlike Panagia Angeloktisti, there is significant dispute about the original design of the monastery nave ceiling, one hypothesis being the presence of the Clerestorey (T_{6a}).

Dayr Anba Bishay (known as the Red Monastery) is a Coptic site in Upper Egypt, near Sohag dating back to ca. 525 AD (T_9). The building has an early Byzantine-inspired foundation and has been kept in a relatively good condition. Several events have shaped the site's appearance including a catastrophic failure of the building possibly due to an earthquake (ca. 800-900 AD, T_8), reconstruction of the outer enclosure wall (ca. 900-1300 AD, T_7), and the ceiling of the nave has long since collapsed (ca. 1670, T_6). The roof's original design has been a much debated topic among the experts at the site; one hypothesis being the presence of a Clerestorey (T_{6a}), and one without (T_{6b}).

So far, on-site experts have been able to identify at least four phases of decorative painting including use of *encaustics* (hot wax painting). The wall paintings date from the sixth to the seventh or eighth century (Late Antiquity) [Bo104]. The soot inside the sanctuary was not caused by domestic activities, but in celebration of the mass, with oil lamps, tallow candle and incense probably contributing the most to the obscuration of the wall paintings.

Since then, a small village occupied within the nave between 1700-1890 (T_5), before it was partially cleared in 1909 (T_4). Medieval renovations, a twentieth century façade (added 1910-1914, T_3) and a dome on the eastern section have contributed to the preservation of the triconch sanctuary (and its wall paintings) [Bo104]. The remainder of the village was cleared between the 1930-1960s (T_2). A full interventive conservation project was initiated at the Red Monastery in 2002 (T_1). Today, conservation is nearing completion (T_0). Figure 12 shows various attempts to recreate the exterior nave at various Timeframes (T_2 , T_3 and T_4). Figure 13 shows a proposed 2D CAD drawings of the past monastery, with the Clerestorey (T_{6a}).

8.2.1. Other Considerations

Similarly to Panagia Angeloktisti, sky models have an impact on the visual perception of a scene. The monastery has considerably less access from which light may enter. This is particularly noticeable in some sky models over others due to the surrounding wall around the nave blocking light from entering on ground level. Lack of access to areas of light makes a considerable visual impact for some scenes, making it appear darker overall, see Figure 14.

As mentioned, it may be advantageous in the first iterations of the CHPR feedback loop to consider physically based believable rendering methods to fast obtain clear general overview of illumination in order to refine and develop plausible renditions. For such instances, using tech-

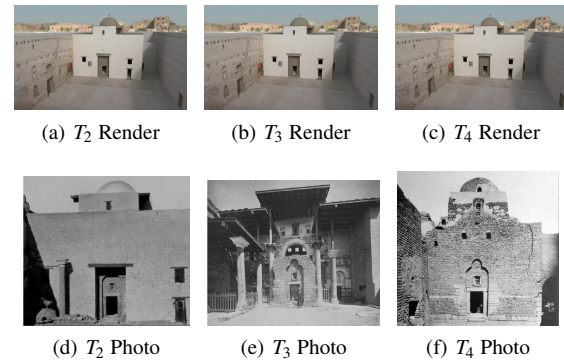


Figure 12: Timeframe renders of the façade.

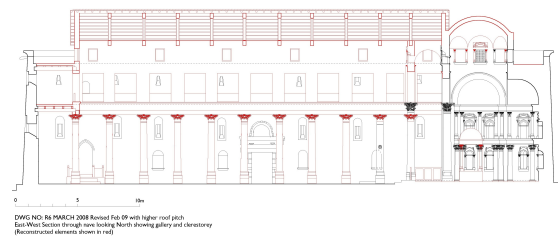


Figure 13: 2D CAD Model of the Red Monastery. Image courtesy of Nicholas Warner and the Red Monastery Project/American Research Center in Egypt.

Figure 13: 2D CAD Model of the Red Monastery. Image courtesy of Nicholas Warner and the Red Monastery Project/American Research Center in Egypt.

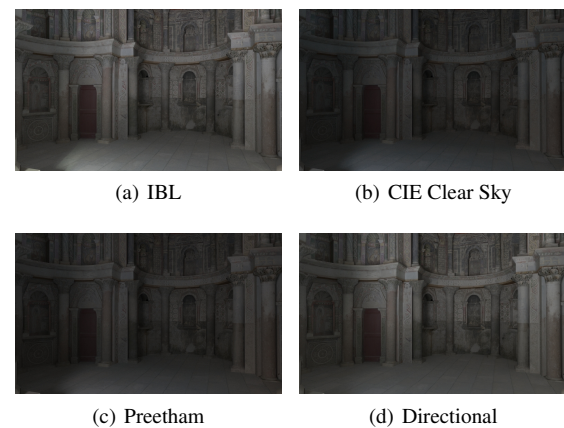


Figure 14: Path Traced sky model examples of Red Monastery (T_0) showing different amount of indirect light.

niques that employ empirically captured illumination may be useful. Image-Based Shooting (IBS) [HBRDC11] used HDR photography to accelerate image synthesis of the interior monastery for previewing purposes, see Figure 15. As estimating BRDFs is not straightforward for such sites, and physical measurement is not an option, the previewing method allows for simple previewing, closer to the ground

truth than what diffuse Path Tracing is able to deliver. Furthermore, it was also shown to be useful to aid CH documentation and 3D model validation to reality.



Figure 15: Comparing Photograph, IBS and Path Tracing.

9. Discussion

Barring the invention of a time machine, or some unforeseen technology, it will not be possible to determine the original appearance of structures with 100% certainty. CHPR may thus appear as a contradictory term because of the equivocal nature of historical reconstruction. Speculative content should be permissible if the goal of the investigation can be met in the presence of such content. For several sociological and archaeological problems, this may be the case. This is unlike traditional Predictive Rendering, where total accuracy is the sole purpose of the whole effort.

9.1. Limitations of Case Studies

Gonioreflectometers are still experimental devices. Their widespread is not likely in the near future. This is a major problem as correct light reflectance models rely on accurate measurement. No portable gonioreflectometers exist in a format that is usable at CH sites. For our case studies, matte materials were approximated as diffuse BRDFs, which is the case for a large number of CH models [HMD*10]. All other glossy and specular materials such as the gold painted icons and the tiled floor in Panagia Angeloktisti were approximated using analytic BRDF models such as Ward and Lafortune [NDM05].

Despite its recognised status as an important historical site, few scholarly publications have been published on Panagia Angeloktisti, limiting the comprehensiveness of our timeline, and lack of branching timeline. The correct modelling of gold mosaics to the specifications of Byzantine environments has not been implemented, despite their importance having been demonstrated through RTI. The Red Monastery on the other hand is currently undergoing significant interventive conservation, with information about the site being updated frequently, which subsequently has been the case for the 3D model as well. In the future we wish to investigate reversing the weathering of the encaustics, and further investigate the nave roof's design.

9.2. Limitations of CHPR

Predictive Rendering is largely a theoretical research framework, developed from technology that is still experimental, 14 years after the original publication. Most graphics groups today do not have the facilities to address all sections of the pipeline. Data acquisition and portability are not straightforward processes either. This may improve as hardware advances in the future.

There are instances in which the full pipeline may not be necessary to investigate the past. Devlin et al. [DCB02] for example, described the relighting of cave art from 15,000 years ago, suggesting that the careful crafting of a horse to the cave wall may have been used to create crude animations of a horse's gait using dynamic flames. In this instance, CHPR would be able to produce a T_0 for the present day and a T_1 with reconstructed points added to the T_0 point cloud based on expert opinion. However, little evidence suggests major damage at several Timeframes, making subsequent T_x s largely unnecessary. No additional information can be extrapolated than what T_0 can already deliver through physical simulation. In this case, only the Historical Properties of the flame and its use are relevant from CHPR.

10. Future Work and Conclusion

In this paper we have proposed an extension to the Predictive Rendering pipeline to study CH in the present and the past. There are several existing efforts towards standardisation in this research domain [3dC09, Gro96, DCM95, AG07, Eur08, IFL09, DH09, GB11, ISO10]. To our knowledge however, no existing ontology have addressed how to best employ rendering techniques to display CH in both the present and past. As CHPR embodies both scene metadata and rendering techniques, we believe a number of these standards however can be employed simultaneously, within the various steps of the Historical Comparison forming predictive results.

Like Predictive Rendering, CHPR is not a fully solved problem. Not all necessary information will be available for interpretation. The pipeline should therefore solely be regarded as a research framework in the attempt to minimise rendering error before, during and after image synthesis. Our solution suggests an iterative and progressive approach based on resources available, but also allows for corrections and updates to be added in a straightforward manner.

Acknowledgements

Thanks to the Byzantine Art Gallery, Ioannis Eliades, Andreas Foulis and the caretakers of Panagia Angeloktisti. Thanks also to the ARCE, Elizabeth Bolman, Nicholas Warner, Agnieszka Szymanska, Laurel D. Hackley, Gerry D. Scott III and Michael Jones', Elmedin Selmanovic, Carlin Yuen and Red Monastery project helpers. Tone Mappers are based on source code by Mantiuk et al. [MKMS07]. CIE Clear Sky and Preetham sky are from Banty's toolkit [Ban06]. Images in Figure 6 courtesy of Elizabeth Bolman. Figure ?? courtesy of Nicholas Warner. RTI in Figure 11 courtesy of Cultural Heritage Imaging.

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