# Virtual Hagia Sophia: Restitution, Visualization and Virtual Life Simulation

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## ABSTRACT

This paper presents a case study centered on the virtual restitution and virtual life simulation of a highly complex and endangered heritage edifice: the church of Hagia Sophia, in Istanbul, Turkey (added in 1996 in the annual list of endangered monuments by the World Monuments Watch). The goal of this article is to describe the techniques used in order to achieve a photo-realistic simulation of the selected space and its characters, as well as to point out the challenges and solutions that such a work implies at different stages in production. Most of these issues are mainly focused on the reconstruction of the architecture of the site, but in order to achieve an accurate simulation the social aspect must not be forgotten. The importance of a heritage site resides as well in the historical characters and the social interactions that were taking place there: this information allows a better understanding of the function and the importance of the selected site in connection with the cultural aspects of the life at a certain time. In order to strengthen the feeling of immersion in a heritage edifice virtually restituted, it is important to recreate virtual life and describe the timely evolutionary aspects of the edifice as well.

**Keywords**: Virtual Cultural Heritage, Hagia Sophia, Virtual Reality, Modeling Techniques, Virtual Humans

## 1. INTRODUCTION

Building a 3D model of a complex heritage site for a virtual reality simulation may become a difficult task when it comes to dealing with hardware limitations. Considerations for the final output of the simulation should be made in order to build the model according to the specific limitations of the selected support. For example if we want the user experience to be limited to a passive walk-trough, we can concentrate our efforts to reproduce precisely all the complexity of the site in a non interactive simulation, but instead if we want the user to be able to freely wander in a 3D real-time environment, a certain balance between the fidelity of the visual reconstruction and the weight of the model has to be found.

In order to achieve a successful realistic 3D simulation of a selected heritage site, different aspects are critical: the choice of the appropriate modeling techniques, the preparation of the lighting models and the texture creation process (which heavily contributes to the surface appearance representation). All these aspects are even more important when the selected space should be prepared for a real-time platform, where issues on the trade-off between frame-rate, and geometrical accuracy of the model must be considered.

The selected site is chosen for its complexity and its importance both as landmark in the Byzantine, Islamic and world ecclesiastical architecture. The history of the building and the subsequent modifications (cathedral, mosque, museum) allowed us to perform a virtual simulation of the restituted space and its evolution through time. The main part of this work describes the virtual restitution of the site as a mosque as it is in the XVI century, and early results of the restitution of the building as Cathedral as it is in the XI century.

## 2. PREVIOUS WORK

In this section selected virtual heritage applications of complex heritage edifices and cathedrals similar with Hagia Sophia are presented.

a) The Real-Time Virtual Reconstruction of Notre-Dame cathedral [DeLeon 1999], based entirely on three-dimensional architectural and photographic data, features an accurate reconstruction and a 3D multi-user virtual reality rendition of the site, accessible to the public from anywhere in the world.

b) The Siena Cathedral [Knöpfle 2000] simulation is an immersive virtual environment that allows the visitors to virtually explore the site, to experience its architecture, dimensions, and atmosphere, and to obtain architectural, cultural, and historical information. A virtual guide, in traditional clothes, talks to the visitor giving explanations about the Cathedral. The presentation is done in real-time on a stereoscopic large-screen projection. In order to achieve a high degree of immersion, the visual representation is complemented by sounds and background music.

c) The Byzantium1200 Project [Öner and Berger 1998] is a non-profit project aimed at creating computer reconstructions of the Byzantine Monuments located in Istanbul, Turkey. It offers a wide collection of reconstructed buildings including the cathedral of Hagia Sophia and other churches and monuments of Istanbul at that time.

In the Byzantium1200 project [Öner and Berger 1998] the 3D model of Hagia Sophia is limited to a non-textured version of the exterior only. In Mark's structural analysis of Hagia Sophia [Mark et al. 1992], only a partial model of the edifice is built, due to its complexity, less detail is integrated and visual appearance of the surfaces of the model is not considered, mainly because the model is targeted for elastostaic simulations and numerical analysis, thus visual accuracy is not a critical factor. Similarly in Kato's finite-element modeling study [Kato et al. 1992], only the first and second domes of the edifice are considered and modeled in 3D: the proposed model is displayed in wire-frame and is targeted for numerical analysis purposes on the elastic deformation of the structure under self-weight.

From the variety of projects and topics we have presented in the above section one can easily see that cultural heritage is a fast growing area of virtual reality applications. Using all the existing technologies in 3D modeling and reconstruction a large number of monuments, museums, and sites are represented through virtual replicates over Internet, on CD-Rom, and trough immersive peripherals such as HMDs and CAVEs. However, large and complex populated edifices are still not widely simulated in their integrality due to their complexity, lack of historical references, and high computational requirements. Recent advances in computer graphics hardware allows easier access to these computational requirements but still a clear methodology is to be drawn for the conduction of virtual restitutions of populated edifices and this is described in the present paper.

## 3. HISTORICAL INFORMATION

Hagia Sophia (exterior depicted in figure 1) represented the apotheosis of Byzantine art and wealth [Kinross 1973]. Lying at the very heart of one of the richest in cultural artifacts cities in the known world, Istanbul, Turkey, Hagia Sophia's rich interior reflects more than fourteen centuries of continuous use first as an orthodox church, then as catholic cathedral, then as mosque, and finally as a secular museum.

The Church of Hagia Sophia was also the Cathedral of the Ecumenical Patriarchate of Constantinople for more than one thousand years. Originally known as the Great Church, because of its large size in comparison with the other churches of the then Christian World, it was later given the name of Hagia Sophia, the Holy Wisdom of Christ, the second person of the Holy Trinity.

Justinian conceived the grandiose project of rebuilding the Great Church from its foundations. Construction work lasted five years (532-537) and in 537 Patriarch Menas consecrated the magnificent church. By an unprecedented combination of structured forms, Justinian's architects (Anthemios and Isidoros) created an immense interior of wide-spanning Vaults and subtly interpenetrating spaces that had never been surpassed.

*Figure 1. Exterior photograph (left) and lithography from the album by the Fossati brothers (right)[Hoffmann 1999]*

## 4. METHODOLOGY

### 4.1 Preparatory phase, data acquisition

All the phases of the constitution of the 3D model are based entirely on two-dimensional archeological, cultural, architectural and photographic data. The data used in the preparatory phase are collected mainly from two different sources:

a) The Yildiz Technical University of Istanbul provided all the cultural and archeological data [YTU Project Team 2001], as well as the architectural plans and sections (shown in figure 2) that are used as a starting base to build the 3D model of the XVI century mosque and at a later stage to virtually restitute the site as a Cathedral of the XI century. Precise measurements were performed, according to these plans, to retrieve the exact dimensions of the main structural elements and were then used in a commercial 3D software package in order to recreate these elements with the maximum precision allowed by the scale factor of the plans.

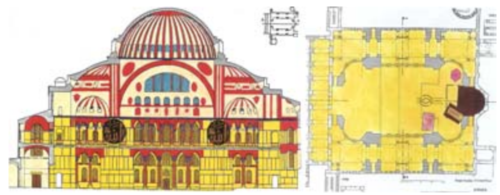

*Figure 2. Architectural plans of the Hagia Sophia building*

b) Since most of the available plans use a large scale factor, between 1:200 and 1:100, high-resolution photographic and video data (samples are shown in figure 3) are collected on site with digital cameras. The digitally acquired data is used as support to model elements not present on the architectural plans due to the scale factor, or to add detail to secondary and small structures that are poorly documented or omitted on the general plans of the building.

*Figure 3. On-site interior photos*

All the photographic data is also used in a later stage as base for the construction and virtual restoration of the material textures.

### 4.2 3D Modeling

Different solutions for the creation of the 3D model of the site were considered but discarded mainly because they would have implied less control over the meshes and the generated number of polygons. Laser scanning was considered but discarded for those reasons. Furthermore its adoption would have been impractical due to the lighting conditions of the selected space and its reflective surface proprieties, and because it would have been necessary to establish far too many measurements points due to the complexity of the building. Photogrammetric techniques have been also discarded because in those conditions they would have produced non-exploitable results (due to poor current condition of various edifice structures). Thus 3D Studio MAX 4.2™ software package was selected for the conduction of the 3D virtual restitution using polygonal modeling techniques (general view depicted in figure 4): NURBS modeling was not considered mainly because the final model is also to be used in a real-time environment.

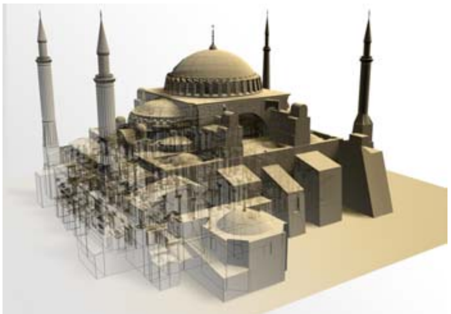

*Figure 4. View of the 3D model with wire-frame details*

Since the final 3D model (figure 5 shows some samples of the interior) is tailored for two different applications, namely a real-time simulation and a non real-time simulation, a balance between the requirements of these two outputs was required. In order to face the challenge of such a complex heritage site, and to prepare it for a real-time simulation, different techniques are used:

a) The model is split in 5 seamlessly overlapping modules that are separately exported in VRML and connected with portals in order to achieve a better frame-rate (only one module at a time is loaded).

b) Larger textures are down-sampled to reduce their size and their loading time.

c) Special care is given to the mesh creation of the critical elements such as the crossing vaults or the chaplets in order to keep the polygon count as low as possible without lowering the visual accuracy of the virtual restitution. To achieve such results many elements are modeled, edited and placed point by point, manually creating the desired facets and adding smooth operators where necessary.

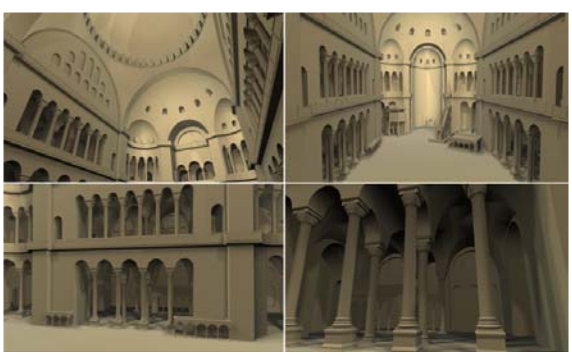

*Figure 5. Non-textured 3D model of the interior*

To cope with the high visual quality expected from a non real-time simulation, highly detailed versions of the textures are mapped on the surfaces of the model (details are described in section 4.3), and special attention is given to the 3D modeling of the main elements and details of the larger surfaces and structures.

## 4.3 Textures

Digital photographic acquisition of the appearance of the surfaces of the building is conducted on site. Due to lighting condition inside the building, its large dimensions and its variable state of degradation (shown in figure 6), ranging from well preserved to highly damaged, only a small part of the collected material is finally directly exploitable for a proper virtual restitution of the selected space.

*Figure 6. Details of the state of preservation of the surfaces inside the building*

Depending on the quality of the collected material, and of the specific surface acquired, two methods are used in order to create the material textures to be mapped on the 3D model: virtual texture restoration or texture composition.

### *4.3.1 Virtual texture restoration*

Virtual restoration is conducted mainly for the decorative elements severely damaged through time or for the acquired textures that are presenting heavy distortion due to the curvature of the corresponding surface during the data acquisition phase, such as the vault's decoration or the main dome's decorative elements.

*Figure 7. Virtually restored textures (upper part) vs. acquired textures (lower part)*

Furthermore virtual restoration is applied where elements belonging to a different epoch had to be removed, such as Christian decorations appearing under Islamic ones (sample results shown in figure 7).

The virtual restoration process, as well as the texture composition process detailed in section 4.3.2, is conducted using the Adobe Photoshop 6.0™ 2D software package. With the support of the light and color specifications of the materials measured on site by the Yildiz Technical University of Istanbul, an effort to retrieve the original color information of the missing elements was attempted. Pixel by pixel editing of the acquired textures is done to clean the images, re-saturate the colors, and fill the missing parts due to degradation. The virtual restored versions of the acquired textures are prepared considering the needs of the UV mapping definition to be applied on the 3D surfaces (a screenshot of the textured model is shown in figure 8), thus distortions in the images are eliminated through 2D editing and sampling of the repeating parts appearing in the textures in order to allow a non-distorted UV planar or cylindrical projection on the concerned 3D surfaces.

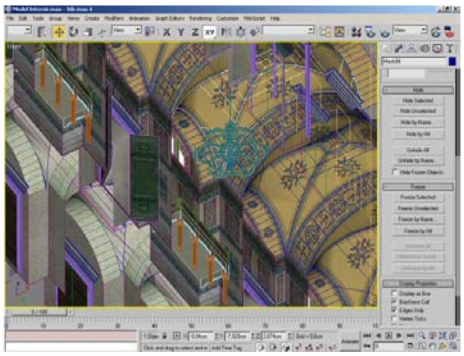

*Figure 8. Screenshot of the textured model during UV editing in 3D Studio MAX™ software package*

### 4.3.2 Texture composition

Texture composition is mainly conducted on the acquired elements that present an acceptable conservation state, such as the marbled walls and the stone columns. Using different views of the selected acquired material as source, 2D editing tools are used to clone, place and retouch exploitable elements in order to build a composed texture as close as possible to its original counterpart. Where necessary, the retouched image is prepared to be tiled seamlessly on the target geometry (figure 9 shows some samples of the composed textures vs. their corresponding source images)

*Figure 9. Composed textures vs. source images*

All the textures produced with the fore mentioned techniques have been prepared at very high resolutions, since it is necessary to have a high degree of precision in order to virtually restitute the textures to their original state in all their complexity. Furthermore the textures are used to produce high detailed renderings for the non real-time simulation of the edifice (figure 10, on the right, shows a rendering of a textured detail). At a later stage the same textures are down-sampled to replace the original ones for use in the real-time simulation.

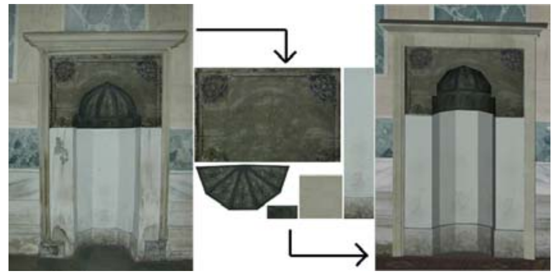

*Figure 10. Texture extraction from a photographic source image (left) and mapping to its corresponding 3D model (right)*

## 4.4 Lighting

Global illumination techniques are used in order to compute a lighting solution for the interior space of the building. During the preparatory phase of the work radiosity computation was considered to perform such a task and, at a later stage, it was tested on a section of the final model with the use of Lightscape 3.2™ software package. Since radiosity techniques imply a triangulation of the surface elements of the 3D model, and precise results are best produced if meshes are built with quads and present a regular arrangement of their facets, when dealing with highly complex surfaces unpredictable results can occur with the appearance of rendering artifacts. Thus such an approach was discarded due to the geometrical particularities of our model, and the necessity to modify the already complex meshes in order to add more polygons to operate the optimization for the radiosity computation. In order to avoid such artifacts the use of a method to compute global illumination, without altering the mesh elements, was investigated. The use of photon tracing, as implemented in the Cebas Final-Render™ Plug-In for 3D Studio MAX 4.2 software package, was finally selected.

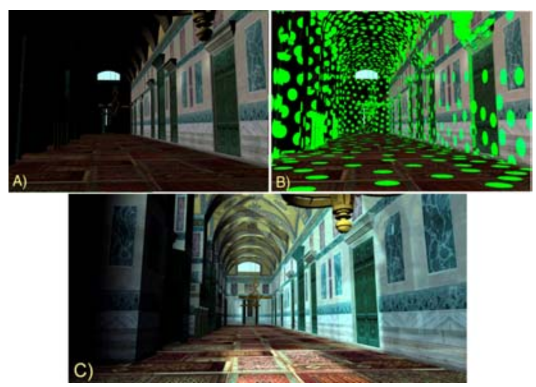


*Figure 11. A) 3D Studio MAX™ direct light, B) Final Render sampling points, C) Photon traced model*

Although this technique is based on ray-tracing principles, it can produce accurate global illumination results visually similar to radiosity computed solutions. Furthermore the possibility to keep track of the photons impact points and of the sampling points on the model (shown in figure 11 B) allows the creation of photon maps to be used in a 3D real-time multitexture rendering engine to modulate the luminosity of the material textures, and thus to achieve a photo-realistic effect.

### 4.5 Restitution of the Byzantine edifice

The Byzantine virtual restitution preparatory phase is carried out by collecting data and joining together all the pertinent sources and the available scientific material, such as architectural and archeological plans, in addition to various works on Byzantine art and architecture. The selected sources provide precise indications for certain parts of the church and describe the lost atrium and various details of other structures lost during the edifice transformations. The 3D model of the exterior of the mosque (depicted in figure 12) is taken as base structure from which all the elements that belong to the Islamic period are removed, then is used as reference for the modeling of the Byzantine structures.

*Figure 12. 3D model of the exterior of the Islamic mosque (left) and of the Byzantine Cathedral (right)*

The main virtually restituted elements are the Atrium and the Byzantine liturgical furnishing (shown in figure 13), located in the interior space of the building, such as the chancel, the ciborium, the ambo, the solea and the synthronon. The drawings and the rest of the collected scientific material, provide the necessary information relative to the arrangement and the architectural description for those parts of the edifice, and enabled us to reconstruct and position each element inside the 3D model.

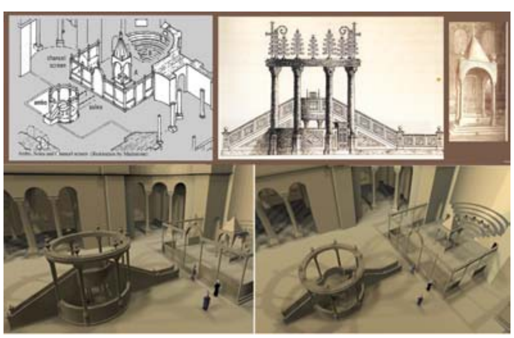

*Figure 13. Byzantine restitutions by Mainstone [Mainstone 1988](above left) and Antoniades (above right) vs. 3D virtual restitution (below)*

Even though the fore mentioned structures are long lost, enough sources are available to perform a geometrical restitution of the selected elements, but on the other hand no specific information is available regarding the surface proprieties and their appearance to perform an acceptable virtual reconstruction of their textures. Therefore the fore mentioned elements, in the current virtual restitution of the XI century Byzantine edifice, present homogeneous surface coloring: investigations are currently conducted to find an acceptable balance between the scientific correctness of the virtual restitution and an enhanced visual impact through the use of material textures.

### 4.6 Bringing the edifice to life

Having virtual embodiments of humans for representing the people of a certain era allows the rendering of realistic simulations of the ancient life with a specific ambience and atmosphere. Such representation has to consider the behavior of the characters, garments and costumes. Therefore careful research on the clothing culture of the ottoman period is carried out and the collected data, such as patterns of different cloths (both male-female as depicted in figure 14) and images of fabrics, are used as base for the restitution of different types of clothes and their simulation around the bodies.

*Figure 14. Sample images of cloths and patterns belonging to the Ottoman period*

The virtual human bodies and clothes are created in order to obtain one unified and optimized model, enhancing the visual impact of the characters with texture mapping and material editing. The 3D generation of the virtual bodies (results shown in figure 15) has also to take into consideration the total number of polygons used to create the meshes in order to keep a balance between the 3D real-time simulation restrictions (once exported in VRML and merged with the virtual edifice) and the skin deformation accuracy of the models (as more polygons deform better but are heavier to simulate).

*Figure 15. Historical source images (left) vs. 3D modeled characters (right)*

## 5. RESULTS

Material produced through the described pipeline is periodically submitted to external supervisors, specializing in Islamic architecture and Islamic art, for validation and feedback. Advice is sought, and corrections are made according to their remarks, mainly for structures and elements poorly documented or omitted in the original source material due scale factor related issues.

The final 3D model of the virtually restituted selected heritage site presents a total of 340.000 polygons subdivided in 5 modules ranging from 20.000 to 140.000 polygons. For the bigger modules, namely the central main hall and the first floor, optimization of the repeating geometrical elements, where possible, should lower the polygon count to an acceptable threshold in order to allow a 3D real-time simulation, currently alternative solutions are being investigated, such as the implementation of multi resolution models of the heaviest geometrical elements.

*Figure 16. Non real-time photo-realistic simulation of the Hagia Sophia building, details of the narthex*

The current state of the virtual restitution covers the modeling of the whole site, both for the Byzantine and for the Islamic periods, and the texturing for both real-time and non real-time photo-realistic simulations, of 3 out of the 5 modules concerning the XVI century restitution (sample images shown in figure 16 and 17). As introduced in section 4.5, texturing issues concerning the XI century restitution are currently being investigated.

*Figure 17. Screenshots of the 3D real-time simulation of the Hagia Sophia building, details of the narthex and side entrances*

Furthermore, even though it was successfully tested on a smaller structure on a real--time platform, the described lighting methodology is currently enhancing only the non real-time simulation.

## 6. CONCLUSION

Virtual restitution of highly complex heritage sites requires accurate choices for each phase of the modeling, texturing or lighting processes and special attention must be used when the models have to be prepared for real-time platforms. Furthermore precise and reliable source data is critical for a scientifically correct and accurate restitution. Interpretative and comparative issues are also necessary when the restitution is targeting lost architectural elements of the heritage site. In the present paper each step of the virtual photo-realistic inhabited restitution of Hagia Sophia in Istanbul, both as Byzantine cathedral and Islamic mosque, is described: common problems, pitfalls, solutions and specific choices are analyzed and explained in order to establish a complete methodology of bringing large, complex and endangered edifices to life and simulating historical characters as well as their architectural evolution. Finally the use of new information technologies, in conjunction and with the essential support of traditional sources and materials, has been presented here in order to describe a complete methodology for the restoration and renovation process of ancient monuments. Hence with the utilization of the mentioned methodology for the situations where architectural restoration and protection are not available, virtual restoration and conservation is exhibited. Such virtual heritage simulations are a fundamental aspect for the full understanding of the historical and social development of vast communities and form a 'virtual material witness' of the process of civilization.

## 7. FUTURE WORK

One of our next goals is to complete the full real-time visualization of Hagia Sophia together with high-quality virtual characters of that time, reenacting a historical scene based on a very precise scenario e.g. depicting a praying sequence. The immersive experience could be heavily enhanced by the addition of 3D rendered sound sequences in order to enhance the virtual acoustical restitution on the edifice. Finally, the adoption of stereoscopic projectors and 3D shutter glasses will enhance greatly the visualization experience.

## 8. ACKNOWLEDGEMENTS

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