

HAGIA SOPHIA - PHOTOGRAMMETRIC RECORD OF A WORLD CULTURAL HERITAGE

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ABSTRACT

The Hagia Sophia in Istanbul belongs with its unique dome construction to the outstanding and extraordinary architectural structures in the whole world. Built between 532 and 537 during the Byzantine Emperor Justinian (527-565), it reflects the sum of all experiences and knowledge of the classical antiquity and it is one of the important monuments of the world heritage. Nowadays the building is under investigation sponsored by UNESCO. New techniques of digital applications in photogrammetry and information sciences open new possibilities for documentation and investigations of such kind of buildings. The Conservation and Restoration Branch of Historical Buildings asked the Photogrammetry Division of the Istanbul Technical University to prepare orthophotos of the Hagia Sophia. Together with the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology, it was decided also to create a high quality 3D model of the dome, so that the obtained results can later be also used in an "Hagia-Sophia Information System". This information system has to collect all information about the building and will be a useful guide for everyone. As one result a 3D photo-model was generated and stored using the data format VRML (Virtual Reality Modeling Language). This paper describes the measurement process, the generation of the 3D model, the production of the terrestrial orthophotos and the setup of an information system.

1 INTRODUCTION

The capital of the Ottoman Empire, Constantinople, was located on two continents. Therefore the artistic style that developed under the Ottomans shows elements of the eastern and western heritage. The Hagia Sophia in Istanbul is one of the most influential buildings of Byzantine architecture and belongs with its unique dome construction to the outstanding and extraordinary architectural structures in the whole world. It reflects the sum of all experiences and knowledge of the classical antiquity and it has been accepted as one of the important parts of the world heritage. Hagia Sophia was since years the focus of all searchers and historians from all over the world. The dome itself, with a span-length of almost 30meters, lies beyond the Roman Pantheon (43m) or Petersdom (42m). But it exceeds them with its space composition in a certain way, that, when entering the building, the structural masses and the load carrying parts are not visible at the first view.

Starting from the proposal of the Conservation and Restoration Branch of Historical Buildings in Istanbul of the Ministry of Culture to prepare orthophotos of the Hagia Sophia before the long time standing scaffold inside the building is removed to another place, the Photogrammetry Division decided in accordance with the Conservation and Restoration Branch to apply the most recent technologies together with the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology and to create a so called 3D photo-model [Kraus K., 1997] of the dome, so that the obtained results can later be also used in an "**Hagia-Sophia Information System**" which will be a very useful tool for documentation. The 3D photo-model is stored using the data format VRML (Virtual Reality Modeling Language). This format was chosen because it enables on the one hand a user-friendly interactive visualization and examination of the data and on the other hand provides a lot of possibilities to link additional information (texts, sounds, movies...) to the 3D model. Besides, most of VRML viewers are available free, so that no additional costs arise for the viewing software.

2 HISTORY OF HAGIA SOPHIA

"Although there are no artifacts confirming it, it is said that Hagia Sophia was built on the site of an ancient pagan temple. Hagia Sophia underwent two phases of construction before attaining its present state. Documents indicate that the first Hagia Sophia was built by Emperor Constantius, son of Emperor Constantinos I, and was opened for services in 360 AD. Although very little is known about this church, it is assumed that it was a basilica-type structure with a rectangular floor plan, circular apse and timbered roof. It was similar to St. Studios, a basilica in Istanbul, the ruins of which still exist. Ancient sources emphasize that the eastern wall was circular. Constantius donated gold and silver as well as religious objects to his church. But Arians vandalized these during the Council of 381 AD. Hagia Sophia was first named "Megale Ekklesia" (The Great Church), as it was the largest church in Constantinople. The historian Socrates indicated that the church was named Sophia during the reign of Emperor Constantius. The name given to the church symbolized the second divine attribute of the Holy Trinity. Originally, Sophia, which means "Holy Wisdom", was a name given to Christ by 4th century theologians. Both names, Megale Ekklesia and Hagia Sophia are used today. The original church was destroyed in 404 AD by mobs, during the riots, when Emperor Arcadius sent the Patriarch of Constantinople, John Chrysostom, into exile for his open criticism of the Empress.

Emperor Theodosius II built a new church, which was completed in 415 AD. The architect of this second church was Ruffinos. The edifice was constructed in basilica-style and had five naves. In common with other basilicas of that age, it had a covered roof. The remains of this church, excavated in 1935, show that a staircase of five steps led to a columned propylaeum in front of the entrance of the building. Including the imperial entrance, there were three doorways in the facade. The results of excavations indicate that Hagia Sophia was 60 meters wide. The length is unknown, since further excavations inside the present-day edifice are not permitted. During the rebellion of Monophysites in 532, Hagia Sophia was destroyed along with many other important buildings, among which were the Church of St. Eirene, Zorzip Bath and Samsun Hospital. After resorting to bloodshed, Emperor Justinian succeeded in saving his throne. This revolt is known as the "Nike Revolt" in Byzantine history, since the rebels repeatedly shouted "Nike", the name of the goddess of victory.

Following these events, Emperor Justinian ordered the construction of a new church, which was to surpass in magnificence all earlier churches. His ambition to make this new church unique, spurred him on to unremitting effort. Historians write that he personally supervised the construction and made full use of all his empire could offer. The two most famous architects of the age; Anthemius of Tralles (Aydin) and Isidorus of Miletus, were entrusted with the construction of the building. They supervised one hundred master builders and ten thousand labourers. The finest and rarest materials from the four corners of the empire were brought to Constantinople to be used in the construction of Hagia Sophia. The porphyry columns previously taken to Rome from an Egyptian temple in Heliopolis, ivory and gold icons and ornaments from ancient temples in Ephesus, Kizikos and Baalbek were among them. The construction was completed in a very short time. It took five years, ten months and four days, from February 23rd 532 to December 27th 537. During the dedication ceremony, Emperor Justinian put aside formalities of state and entered the church excitedly, to say a prayer of thanks to God for allowing him to fulfill his dearest wish. He cried with pride, remembering the temple in Jerusalem "Oh, Solomon, I have surpassed thee".

Later, the church was damaged many times by earthquakes and fires, and had to be repaired and reinforced. On August 15th 553, January 14th 557 and May 7th 559, earthquakes destroyed the eastern side of the dome. The nephew of the original architect, Isidorus, repaired the damage. He increased the height of the dome by 2.65 meters and built buttresses in the form of towers to support the dome. On February 9th 869, during the reign of Emperor Basil I (867-886), an earthquake damaged the western side of the building. It was repaired in 870. On October 25th 986, a violent earthquake resulted in the collapse of the western apse and caused partial damage to the dome. The church had to be closed until the architect Tridat finished repairing it in 994. In 1204, the Fourth Crusaders sacked the church. During the Palaeologian age, Emperor Michael VIII (1261-1282) had Hagia Sophia repaired by the architect Ruchas, and the buttresses in the southwest were added at that time. In 1317, during the reign of Emperor Andronicus II, the north-eastern and south-western walls were reinforced on the exterior by pyramid-shaped buttresses. In 1348, the eastern half of the dome collapsed and was afterwards repaired. In the first half of the 15th century, travelers and other sources described Hagia Sophia as being in a state of disrepair.

When the Turks conquered Constantinople in 1453, the church was converted into a mosque, a place of Islamic worship. To begin with, Turks preserved the frescoes and mosaic figures of Christian saints, which decorated the walls. However, in the 16th century, these were completely covered by plaster, since the Islamic code forbids figural representation. After it became a mosque, the following changes, necessitated by Islamic architectural standards, were made: Sultan Mehmed II "the Conqueror" built an altar (mihrap) in the east, since the apse should be in the direction of Mecca and the brick minaret on the south-east corner of the edifice. Sultan Bayezid (1484-1512) added a minaret on the northeast corner. The Turkish architect Sinan, built the two minarets in front of the church during the reign of Sultan

Murad III (1574-1535). Murad III also had water urns of the Hellenistic period (300 BC) brought to the mosque from Bergama. The pulpit (minber) and preacher's pew (muezzin mahfili) were added to the interior during the reign of Murad IV. In 1739, Sultan Mahmud I built a library and a primary school (mekteh-i sibyan) in the south. In 1850, Sultan Abdulmecit added the present day Imperial Pew. During his reign (1833-1861), important repairs were entrusted to the Swiss architect Gaspare Fossati. He removed the plaster covering the mosaics and then replastered them. He decorated these newly plastered areas with frescoes. The building was completely renovated inside and out. An horologion was built to the south of the structure. In 1926, the government of the new Republic of Turkey, appointed a technical commission to investigate the architectural and static state of the building thoroughly. According to the commission's report, the foundation of the structure rested solidly on a bed of rock. Following Kemal Ataturk's orders, Hagia Sophia was converted into a museum on February 1st 1935. Ataturk visited the museum a few days later, on February 6th 1935." Taken from: ["Focus on the World", 2000]



Figure 1. A general view of Hagia Sophia

3 RELATED WORKS

The United Nations Educational, Scientific and Cultural Organization (UNESCO) Convention concerning the protection of the world cultural and natural heritage has accepted Hagia Sophia by the Ninth Ordinary Session, in UNESCO Headquarters, Paris, 2-6 December 1985 of the World Heritage Committee as a World Cultural Heritage. The brief description of the acceptance is as follows: "Strategically located on the Bosphorus peninsula between the Balkans and Anatolia, the Black Sea and the Mediterranean, Istanbul has been associated with major political, religious and artistic events for more than two thousand years. Its masterpieces include the ancient Hippodrome of Constantine, the 6th-century Hagia Sophia and the 16th century Suleymaniye Mosque, which are now jeopardized by overpopulation, industrial pollution and uncontrolled urbanization." [UNESCO, 1985]

Nowadays the building is under investigation sponsored by UNESCO. Today there is a great restoration work, especially for the mosaics at the huge dome, in the building supported and controlled by the Conservation and Restoration Branch of Historical buildings in Istanbul of the ministry of Culture .To carry out the restoration of the dome there is a long time standing scaffold erected under the quarter of the dome. There are many other projects planned and carried out by many organizations and universities from many countries all over the world. One of the projects supported and realized by the Princeton University [Dunlop J., 1997] has the aim to determine the susceptibility of the structure, especially its large dome and arches, to collapse due to the earthquakes that often strike that part of the world. Another site, where information about Hagia Sophia is available is The Great Buildings Collection [Matthews K., 1999]. There 3D models, photographic images and architectural drawings, plus commentaries, and bibliographies of hundreds of buildings can be found.

As mentioned before there are many works on Hagia Sophia for demonstration and searching purposes. Besides the demonstrating and searching purposes new techniques of digital applications in photogrammetry and information sciences open new possibilities for documentation and investigations of such kind of buildings. On one hand it gives us

the possibility to present our results in different media. On the other hand, by establishing a 3-D model and an information system based on the spatial information of the building, the users of this kind of technologies have the possibility of working in different scales without losing the relations of the whole structure. The 3D Model of high quality obtained by photogrammetry will be used as the base data of an Information System, which will contain all graphic, semantic and raster data belonging to Hagia Sophia. This Information system has the duty to collect all the information about the building and will be a useful guide for everyone.

4 GEODETICAL AND PHOTOGRAMMETRIC MEASUREMENTS

The complex geometrical form of the dome has been surveyed with the help of photogrammetric methods by employing the metric camera WILD P31 with color and B/W films. Selecting the right film material in order to obtain the most natural color became a crucial decision. When working with floodlight that illuminate the dome surface a film for artificial light is needed. Unfortunately, at fine weather sun light through the top windows of the upper gallery is predominant causing natural light conditions. The situation again changes as soon as clouds cover the sun. As it is not possible to work in the evening the optimum choice of films depends very much on the current weather and may be adapted several times a day.

During a period of 3 days a total of 30 monochrome photographs (using a Kodak TMX 100 film) and 50 color photographs (30 using an Ektachrome 100S for natural light and 20 using an Ektachrome 64T for artificial light) were taken of the great dome and the adjoining smaller domes. Finally, for the modeling process 17 color photographs were chosen. 3 photographs were taken from the floor looking upwards to the dome using a focal length of 100 mm. The other 14 photographs were taken from the scaffold using the same objective. To cover the whole visible area of about 300 gon the P31 camera was positioned on the scaffold at the center of the dome and after each photograph rotated about 42 gon. So, 7 photographs were taken at a height of about 43 m. The other 7 photographs were taken in the same way but at an height of 39 m. This results in 3 stereo models with a horizontal base on the floor and 7 stereo models with a vertical base on the scaffold.

For image orientation and scaling 68 points located on the lower gallery as well as on the meridional arches of the dome were resected from points of a polygon established on the gallery of the dome (Figure 2). The points on the meridional arches and on the front face gallery were resected with the electronic theodolite Pentax ATS 102 from nine polygon stations lying in the gallery of the dome. All these points are defined in an overall coordinate system with the origin lying on the entrance floor of the building. Not to confuse the similar points on the meridional arches another person signalized them with a laser pointer each time during measurement. The measurements were adjusted simultaneously and the co-ordinates of the points on the meridional arches and the gallery are determined with a root mean square error of ± 1 cm.

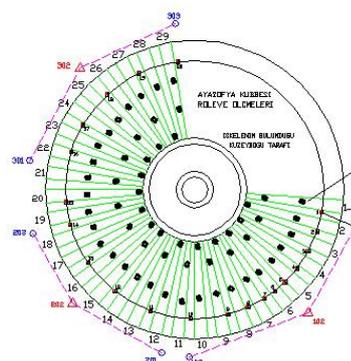


Figure 2. The measured points on the meridional arches of the Dome and the Polygon Stations. On the upper right part no measurements could be done because of the scaffold.

5 OBJECT MODELING AND ORTHOPHOTO PRODUCTION

The 10 stereo models were oriented using the 68 control points and evaluated on an analytical plotter Wild BC3. Apart from the Arabian strokes at the center of the dome and a great number of single surface points also the breaklines at the meridional arches were measured in order to get a high quality model of the complex geometrical form of the dome (Figure 3). In total more than 6000 points were determined by stereo restitution.

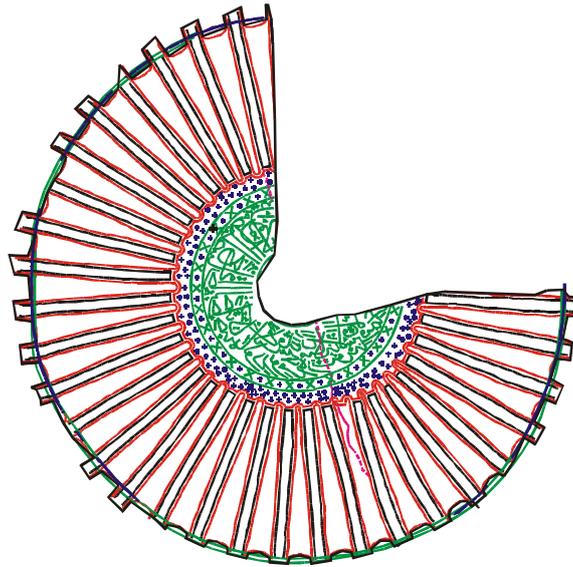


Figure 3. measured breaklines and Arabian strokes

Next, the different stereo-models were fitted together resulting in a 3D data set consisting of points and line information. This data set was then triangulated to build the 3D model consisting of about 12000 surface patches. Based on this model a photo-model and digital orthophotos of the dome were produced. Therefore the P31 photographs were scanned at the Zeiss PhotoScan PS1. The photographs taken from the floor were scanned with a resolution of 15 microns and the photographs taken from the scaffold with a resolution of 30 microns, which in both cases corresponds approximately to 0.5 cm on the surface of the dome.

Whereas the interior orientations had of course to be re-measured for the scanned images the exterior orientations were taken from the stereo models of the analytical plotter. The 3D model was then projected back into the digital images using a rough model of the scaffold to estimate image areas occluded by the scaffold (Figure 4). Nevertheless some interactive rework had to be done to eliminate points in fact not visible. Back projection and interactive rework was done using the photogrammetric plotting software ORPHEUS [Kager H., Rottensteiner F., 2000], developed at the Institute of Photogrammetry and Remote Sensing in Vienna.

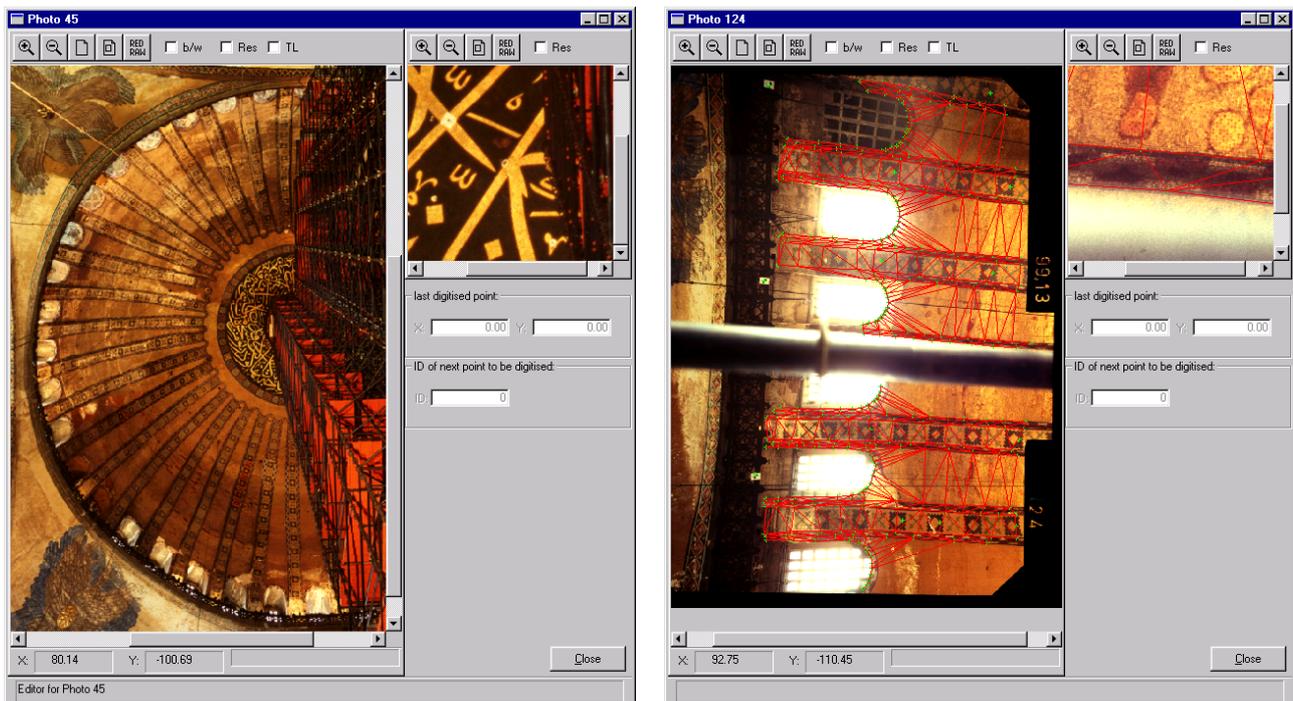


Figure 4. left: photograph taken from the floor with scaffold as viewing obstacle
right: part of the dome hidden by one pillar of the scaffold

The production of the orthophotos was also done using a software program developed in Vienna . In contrast to conventional 2.5D orthophoto software, this program operates on a full 3D data base and allows any arbitrary spatial position of the orthophoto image plane. The definition of the orthophoto planes was done by approximating the visible part of the dome by a polyhedron (Figure 5). The projection itself was performed orthogonal on to the facets of the polyhedron. For each of the 59 facets one orthophoto was computed for an output scale of 1:25.

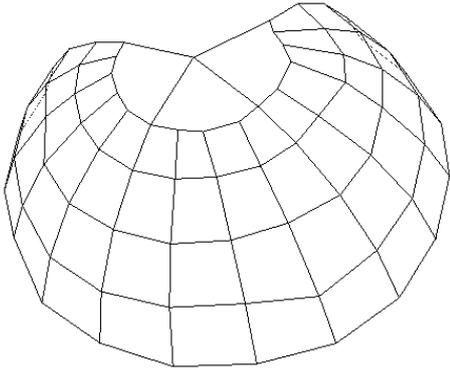


Figure 5. polyhedron used for orthophoto production

6 VISUALIZATION AND INFORMATION SYSTEM

For visualization a 3D photo-model was generated and stored using the data format VRML. VRML is an acronym for "Virtual Reality Modeling Language". It is the international standard file format for describing interactive 3D worlds and objects on the Internet [Carey R., Bell G., 1997]. It is in fact the 3D analogy to HTML. This means that VRML serves as a simple, platform independent language for publishing 3D Web pages. Using this possibility of making VRML worlds available over the internet a great public can access this kind of 3D information.

To be able to view such a 3D scenes a VRML-Viewer is necessary. This viewer can either be a standalone program or it can be integrated as a plug-in into a HTML-Browser. There are a lot of such viewers on the market for every current operating system. Because most VRML viewers are available free no additional costs arise for the viewing software. Within such a scene the user can interactively move around and examine the virtual world (Figure 6). Of course some viewpoints and key-positions can be defined and then an automatic flight through the scene can be animated in real-time.

By using VRML additional information apart from geometry and texture can be linked to the 3D model. This information can be in the form of text documents, sound sequences, movies or even other VRML scenes. All aspects of virtual world display, interaction and internetworking can be specified using VRML. Using these possibilities 3D photo-models combined with VRML technology have a very broad applicability as for example distributed visualizations, interactive environments, interactive simulations for education, virtual museums, and more.



Figure 6. Visualization of the photo-model using the VRML viewer CosmoPlayer

Besides this pure visualization it is often desirable to have possibilities to react on user inputs. These inputs can be mouse-clicks within or without the VRML world or just the movement of the virtual user walking through the VRML scene. By using special objects - called nodes - VRML provides different methods to react on user commands. In connection with an information system the most important nodes are "Anchor", "Inline", "Sensor" and "Script". [Dorffner L., 1999]

- **Anchor:** Similar to HTML VRML also allows access to other files using an Anchor-node which serves as hyperlink. Each object of a VRML scene can be used as Anchor. By clicking on such an object the scene is replaced by the selected Web address (HTML file, other VRML world, ...). In a 3D information system a mouse-click on a door, for instance, may change to a photo-model of the room behind this door. The hyperlink may concurrently also open a HTML page showing additional information about a selected painting or wall mosaic.
- **Inline:** The Inline-node allows the inclusion of another VRML file stored anywhere on the Web into the current VRML scene. So very large and complex photo-models can be split into smaller parts leading to a higher performance during visualization and simplifying the problems of updating the model. Besides, photo-models generated at different time-stamps can be visualized simultaneously for comparing variable states of an object.
- **Sensor:** Sensors are special VRML-nodes which generate events when the user interacts with them. This can happen by a mouse-click or by moving the cursor over an object of the VRML scene. This event is then passed to other nodes (for instance JavaScripts) which then launch some action (starting of an animation, playing of some audio- or video-clips). Events can also be generated just by the movements of the virtual user within the scene. In reaction on such movements different levels of object resolutions can be loaded, depending on the distance and visibility of parts of the model with respect to the current position of the virtual user.
- **Script:** Script nodes allow the world creator to define arbitrary behaviors, defined in any supported scripting language. The VRML 2.0 specification defines Script node bindings for the Java and JavaScript language. Scripts are used in animations where position and orientation of the camera have to be interpolated depending on predefined time-stamps. When measuring coordinates, angles or distances on the photo-model Scripts are used to perform the type conversions that become necessary to display the measured values on the screen (Figure 7).



Figure 7. Detail of the dome showing a modeled structural fissure (also visible in Figure 4) and the measured coordinates at the cursor position as well as a measured distance marked at the bright line.

Up to now all mentioned possibilities are limited to interactions within a VRML scene. Concerning information systems it is also necessary to be able to control the scene from outside. This can be done using the EAI (External Authoring Interface) [Marrin C., 1997]. This interface allows programmers to establish a connection between a web page and an embedded VRML browser window, thus providing a possibility to manipulate the VRML scene depending on user requests on the web page [Zeisler Ph., 1999]. Using this possibility the interactivity is not limited any more to the purely VRML scene but also external systems, as for example data bases, can be connected. In this way, the VRML model can be used as kernel of an interactive spatial information system. [Landes S., 1999]

7 CONCLUSIONS

A world cultural heritage, like Hagia Sophia, is to be presented worldwide. Politicians, managers, scientists and interested non professional people should be able to get general and detailed information about such buildings or sites. Therefore an information system based on Web standards seems to be suitable. By using the 3D standard VRML photo-models can be made available over the internet to a great public without additional cost for a viewing software. Using the possibilities of linking additional information apart from geometry and texture to the photo-model complex spatial and thematic situations can be presented vividly. In this way, the photo-model becomes the kernel of an interactive spatial information system.

The intended goal of this project is to document the whole building in an "Hagia-Sophia Information System" which will contain all information belonging to Hagia Sophia and shall be a useful guide for everyone. By using VRML we want to encourage the users accustomed to classical methods to develop themselves. This project proved the applicability of the new technology for studies of that kind..

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