Reality-based 3D modeling of the Angkorian temples using aerial images

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Abstract

The UNESCO world heritage site of Angkor in Cambodia houses more than 1000 historical structures within a vast area in the northern lowlands of the Tonle Sap Lake, where the Khmer empire had its center between 800 and 1327 A.D. The goal of this work was to check the possibility to derive detailed and reality-based 3D models of complex historic buildings from aerial images. JICA (Japan International Cooperation Agency) provided to the institute a block of 55 mostly black and white copies of an original set of 357 aerial photos. The images cover an area of approximately 5.3 x 5.4 km that includes the temples of Angkor Wat, Bayon and Phnom Bakheng. The average scale of the photos is 1:5100 and those displaying the main temples are in color. For photogrammetric processing, the photos were digitized with a resolution of 15 µm. For the image triangulation, geo-referencing, digital elevation model and ortho-photos generation, and for the texturing commercial and in-house programs were used. The final accuracy of image measurements achieved after the photogrammetric triangulation was $\sigma_0 = 7.3$ µm.

The produced Digital Terrain Model (DTM) displays a completely flat area, only interrupted by the Phnom Bakheng hill and the artificial banks surrounding the moats of the temples. For the 3D reconstruction of the temples, manual stereo measurements were performed. The resolution of the available images was not sufficient for a detailed modeling of the entire area, therefore mostly horizontal surfaces were measured and the walls were extruded to the ground. Nevertheless, one of the first 3D models of the Angkor area based on aerial images could be produced. In addition to four large temples, a variety of about 30 other structures, such as walls and modern houses, were reconstructed in 3D, the temple of Ankor Wat was taken as an example for texturing from aerial pictures.

1 Introduction

The documentation and visualization of large Cultural Heritage sites has become a very interesting and challenging research field in the recent years. Photogrammetry, the science of obtaining reliable measurements from images, is nowadays much more frequently used to generate visualization and animation products, documentation material for conservation, restoration and future planning as well as traditional maps of the investigated areas. This is mainly due to two facts. On the one hand, UNESCO is paying more attention to large cultural and natural sites: the ‘Open Initiative’ partnership was started with different space agencies to support and assist in the monitoring and documentation of World Heritage sites, natural hazards and for sustainable development using satellite data. On the other hand, a wide array of new technologies is nowadays available which greatly support the efficient generation, administration and analysis of such models. From the technological point of view data from high-resolution satellite sensors and digital aerial cameras are increasingly becoming available. Moreover, the automation of the photogrammetric processing chain has made great progress recently and different commercial software is nowadays available for non-expert users. In addition, Geographic Information System (GIS) technology provides many tools for data administration and analysis.

. In the following sections, after a geographical and historical introduction to the Angkor site, the related works in the archaeological area will be summarized. Descriptions of our photogrammetric processing and modeling as well as conclusions end up this paper.

2 The UNESCO WH site of Angkor

Angkor is located in the central part of Cambodia, north of the Lake Boeng Tonle Sab, in the province of Siem Reap. The historic area spreads out over a largely forested and completely plain area of approximately 400 square kilometers, and only a few hills interrupt the plain. Angkor Archaeological Park contains the magnificent remains of the different capitals of the Khmer Empire, from the 9th to the 15th century. Many of the hundreds of ruins are still covered by vegetation and only a few, such as the famous temples of Angkor Wat and Bayon (at Angkor Thom) are under cultural heritage preservation. In 1992, the Angkor Archaeological Park was included into the UNESCO World Heritage List. Nowadays, UNESCO has set up a wide-ranging program in order to safeguard this symbolic site and its surroundings, nevertheless, many problems concerning its maintenance still remain.

3 Historical background

The early culture of Angkor, nowadays known as Cambodia, had socially and religiously developed under Indian influence and formed a society based on Hinduism. The rise of the Khmer empire began 802 AD, when they liberated themselves from Java to become the Kingdom of Kambuja. In its largest expansion, the Khmer ruled over an area that included the actual Cambodia and Thailand and even parts of Laos and Myanmar. Arts and architecture was influenced by Hinduism and later by Buddhism; this mixture of styles is visible at several temples, as some of the art also had been destroyed or redesigned with a new ruler. Today the only visible structures of the ancient Khmer empire are the sandstone built sanctuaries, because “[…] domestic dwellings have been built in […] predominantly perishable materials” (Jacques, 1997) and not much remains today of the large cities which had spread around the temples but postholes.

The first Khmer capital surrounded the area’s only larger hill with the central sanctuary Phnom Bakheng, built in 889-910, towering 60 m above the surroundings. Baphuon temple was built in the 11^{th} century over a small mount north of Phnom Bakheng.

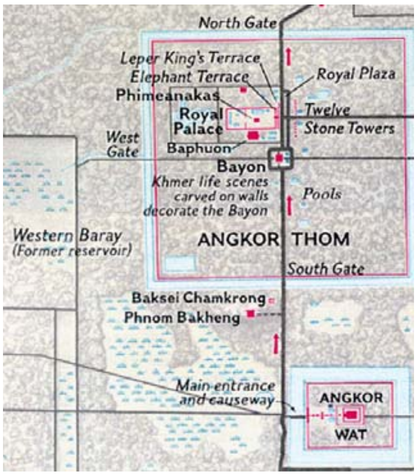

Fig. 1: Map of central Angkor, showing coverage of aerial images. Ruins of the Bayon temple (1181-1291).

Chinese historic documents state that the collapsed ruins were in the time of the Khmer covered with bronze plates. In the years 1113-1150 Angkor Wat was constructed, and until now it is one of the largest single religious structures in the world. As the translation of the name “the capital which is a temple” reveals, it contained a royal palace as well as the main sanctuary which was probably designated to Vishnu (Jacque, 1997). The structure gives an idea about Hindu cosmology with the five central towers standing for Mount Meru, the Hindu Olymp, the outer walls representing the mountains at the worlds end and the moat as the ocean beyond. The capital was relocated various times until Angkor Thom, “the great town”, just north of the hill of Phnom Bakheng was founded 1181. The temple of Bayon was constructed in the years 1181-1219 a few kilometers north of Angkor Wat and close to Baphuon, in the centre of Angkor Thom as its main sanctuary; a magnificent piece of architecture in the style of Mahayana Buddhism that symbolized a Lotus-Blossom (Jacque, 1997).

The last known stone inscription dates from 1327. It is assumed that due to the adoption of Theravada Buddhism in the 14th century, the ruler had lost the godlike position he had been in before. Therefore, no more large sanctuaries were built for his obeisance and the great architecture and the canal system was not maintained anymore. The rise of the Thai and their conquest of Angkor in 1431 is “the traditional (and probably inaccurate) date of what has been called the *abandonment of Angkor*” (Jacque, 1997), when the Khmer rulers had to move their capital to the southern part of their reign. There were several attempts to inhabit the area again, but droughts and floods and the advancing forests had probably destroyed the unguarded water system and within the centuries forests covered the temples. French archaeologists visited the site in the 19th century. Since then various groups have excavated, reconstructed and preserved parts of the temples. A difficult task not only because of the vast area and the huge structures but also because of the political struggle Cambodia had been in the last century and which interrupted the work for several decades.

4 Related works in the study area

In the civil war the ruins were severely damaged, mostly due to art robbery. Nowadays the landscape has changed dramatically because of population growth and increasing tourism. This makes further protection of the historic sites necessary.

Several international teams have been or are working in cooperation with UNESCO, the local APSARA Authority and Cambodian universities on projects to safeguard the temples of Angkor, which include exchange projects and training of local experts and students. Besides the reconstruction work, a variety of remote sensing and photogrammetric methods were used to digitize the temples for cultural heritage purposes. A selection will be briefly introduced in the following (Tab.1):

- *Japanese Government team for safeguarding Angkor* (JSA, 1995-2005): within this project the northern library and other parts of Bayon were restored. A JICA flight campaign from 1997 produced detailed regional maps (1:5000). Keio University (Japan) used satellite data and kinematic GPS for a 3D digital reconstruction of Bayon and Angkor Wat (Watanabe et al., 1999). Sophia University (Japan) laser-scanned several statues, and Tokyo University scanned the whole Bayon for a complete high-resolution reality based model (Ikeuchi et al, 2004, Kamakura et al., 2005). Moreover, a field campaign with a balloon flight delivered pictures of Bayon.

- *German APSARA Conservation Project* (GACP, 1995-2000, University of Applied Sciences, Cologne) works on the preservation of the APSARA relief of Angkor Wat (Leisen, 2000).

- The *Angkor Project Group* (APG, University of Heidelberg, Germany and Royal University of Fine Arts and Architecture, Phnom Penh, ongoing since 2005): concentrates on 3D-CAD modeling and terrain visualization based on 2D maps and digital images,

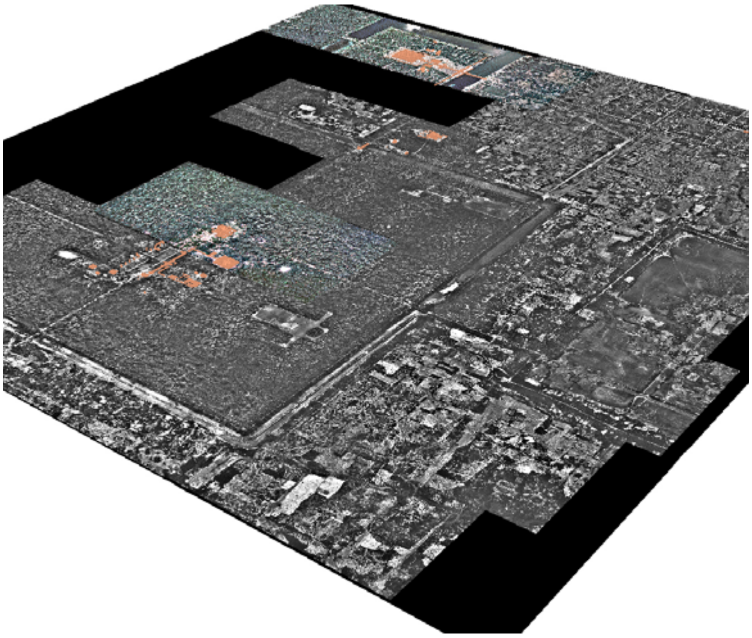

Fig. 2 The orthomosaic combines all aerial pictures that were included in the modeling. In the front lies the northwest corner of the Angkor Thom moat, in the far back is the temple of Angkor Wat. The blackened areas represent missing images in the available data set or images that could not be included due to orientation problems.

focusing on the temples Bayon and Phnom Bakheng for reconstruction purposes.

- The *Banteay Srei Conservation Project* (BSCP, 2001-2005): in collaboration with the Swiss Agency of Development and Cooperation; the aim was to restore the Banteay Srei temple (Gerber & Sauer, 2003).

- *Greater Angkor Project* (GAP, 2001-2010, École française d'Extrême-Orient (EFEO), and University of Sydney): a variety of studies have been launched about the decline of Angkor which include mapping missions (RADAR data and aerial images were acquired in collaboration with JPL-NASA), on site investigation about the water system and the perished cities of the Khmer (Fletcher et al., 2003 and 2004) and detailed 3D-modeling of several sites.

- *Living with Heritage program* (LWH, inter-disciplinary program of the University of Sydney): the focus lies on present cultural heritage preservation.

5 Photogrammetric modeling at ETH

The institute's first work in the Angkor area was the digital reconstruction of a smiling Buddha tower in Bayon (Visnovcova et al., 2001). Terrestrial amateur images were used to automatically create a 3D model of the tower.

Our actual work is instead related to aerial images, acquired in 1997 during the Japanese flight campaign for the „Topographic Mapping of the Angkor Archaeological Area". A Leica RC 20 aerial camera with a focal length of 153.18 mm was used for the project. Approximately 350 images were acquired from a flight altitude of about 780 meters above ground at an image scale of 1:5100. 60 mostly black and white copies were available for our purpose. The images cover an area of about 5.3 x 5.4 square kilometers, starting from the east end of the large water basins of the West Barray to the east of the Angkor Thom city moat. The most northern pictures include the northern moat of Angkor Thom, to the south they are bounded by the southern moat of Angkor Wat. The photos are arranged in seven strips with seven to ten photos each. Only eleven of these pictures are colored and those cover the main temples Bayon and Angkor Wat.

All photos were digitized with a resolution of 15 microns using a photogrammetric scanner Vexcel Ultra Scan 5000. Tests with a 10-micron scan did not offer a higher quality of the digitized image. Only three of 22 original ground control points (GCP) from the flight campaign were located within the area of interest, therefore additional GCPs had to be found. Besides this, the image strips have a poor overlap of approximately 20%; hence most of the area, including the majority of the temples, is covered only by one strip. With this little overlap, the resulting orientation achieved by aerial triangulation would have been unstable. A solution for additional GCPs was found by using the digitized GIS map created in 1997. After bundle adjustment, a final global orientation accuracy of σ_0 = 7.3 μm was achieved. The average correction of control points had a RMS horizontal error of 1.66 m and a vertical RMS error of 1.31 m. Due to the strong vegetation inside the moat of Angkor Thom, problems occurred during aerial triangulation for several images and in the successive generation of a digital terrain model (DTM) and orthoimages. Therefore, two images were not included. The resulting DTM, textured with a single large grey scale orthoimage which is overlaid with colored orthoimages in the areas of Bayon and Angkor Wat, is shown in Fig. 2. The reconstruction of the main architectures of the Angkor area was afterwards performed by means of stereo-measurements on the oriented images.

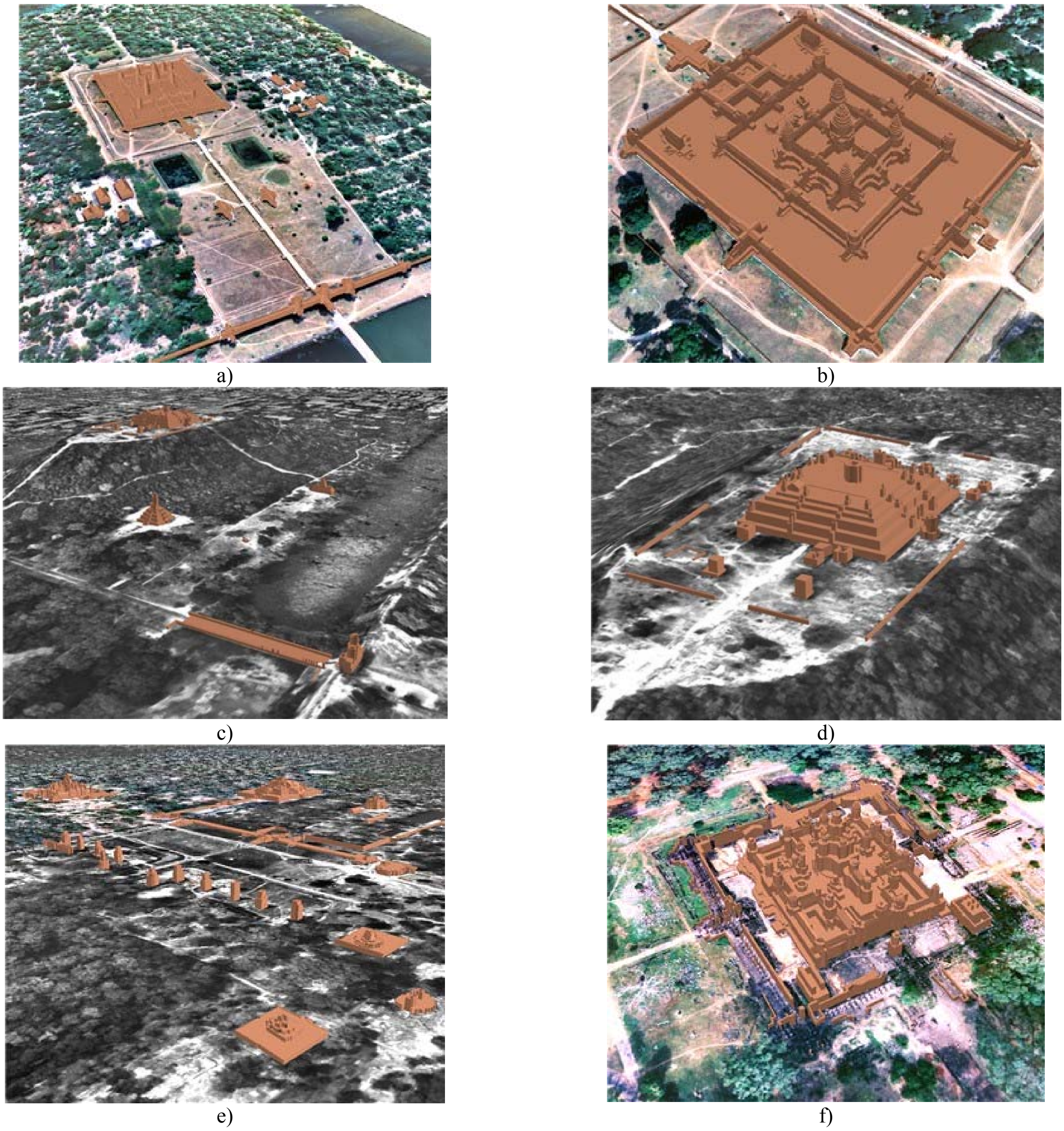

Fig. 3 a) Angkor Wat from bird view **b)** Angkor Wat **c)** Phnom Bakheng hill with surrounding temples **d)** Phnom Bakheng **e)** Angkor Thom with the temples of Bayon and Baphuon in the background **f)** Bayon temple.

Viewing and measuring in stereo allow a better reconstruction of the object of interest and increase the reliability of the product. Mostly rooftops and inclined walls were outlined while, due to the low resolution images, the very detailed areas were simplified. To construct vertical walls of the temples, the measured horizontal outlined features were extruded from the top to the DTM base. Strong shadows that darken the north side of the buildings and the 20% overlap of the strips sometimes made a full model of the buildings impossible. Several attempts with different programs and additional ground control points extracted from the Japanese GIS map did not provide better results.

The texturing was accomplished with in house software. The cropped part of the aerial image together with the field of view and the TIN (Triangle Irregular Network) of facets provide the required information to start a GPU-based off-screen planar orthographic image mapping. The gained texture coordinates define the connection between the cropped image and the 3D model. The field of view is rendered using OpenGL and hardware acceleration. A low resolution textured model is displayed on the institutes homepage.
http://www.photogrammetry.ethz.ch/research/angkor3D.

For more detailed textures and for the side parts of the buildings, images from near surface photogrammetry would be of advantage.

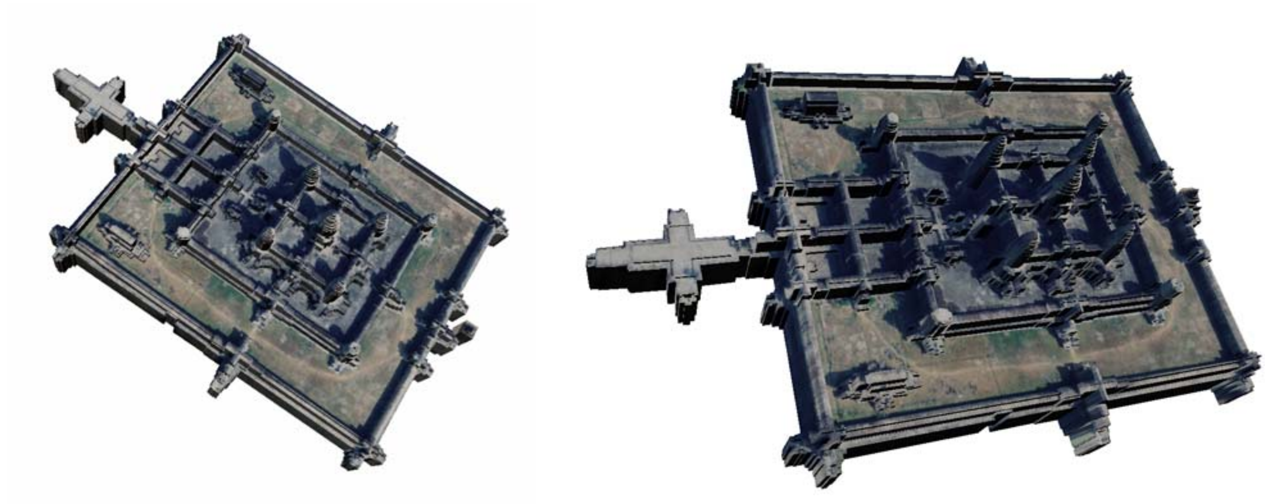

Fig 4. Textured model of Angkor Wat.

6 A comparison with other data sources

The used aerial image data has a footprint of approximately 20 cm (pixel size of 15 μm). This value is not enough for an accurate and detailed digital reconstruction of non-rectangular or non-well preserved complex buildings. Very detailed structures had to be simplified in the modeling phase; neither entrances nor pillars with roofs can be displayed, as walls had been extracted from the rooftop to the ground. Certainly more accurate models could be generated with larger scale aerial images of using acquisition platforms like UAV or balloons and the use of additional terrestrial imagery. Nevertheless, the main structures could be successfully extracted with the available data, as it can be seen in Fig. 4. The question comes up if there is a possibility to use high-resolution satellite imagery for the modeling of similar sites. These image data are nowadays competing successfully with traditional aerial imagery, especially for the purposes of DTM generation or terrain study in such problematic areas. Nevertheless, regarding *Quickbird* or *IKONOS* data, as visible for example in Google Earth (Fig.5), even the high resolution of these images is not sufficient for architectural modeling, as it can be achieved with aerial imagery. Even with a set of stereo images, a detailed reconstruction of complex architectures as it is found in Angkor cannot be achieved at comparable accuracy. The Greater Angkor Project is currently preparing a super light plane flight campaign to take high resolution aerial images of the area, which could be an interesting comparison.

7 Further studies

At the Photogrammetry and Remote Sensing Group of ETH Zurich, the complete set of the aerial balloon images of Bayon is available. By including this data in the already processed one, parts of the 3D model could be improved significantly. Additionally, the complete set of aerial images was not used for modeling purposes yet. As there are various important archaeological sites within the surrounding area, this could be a promising approach to contribute to a better understanding of the temple allocation.

8 Conclusion

In this contribution we have presented the reality-based 3D modeling of some complex architectures of Angkor, Cambodia. The digital reconstruction, performed from a set of non-optimal aerial images, was overall successful, orthoimages of the complete area were derived and 3D models of several temples have been produced. The very few ground control points (GCP) in the original data, the strip overlap of 20%, the strong shadows in the images and the dense forest cover of the central part of Angkor Thom made the triangulation of all images and a full modeling of the structures an extremely difficult task. The very detailed and richly decorated architecture of the Khmer culture complicates the modeling with aerial photographs as well.

A complete series of colored images would have been of advantage for finding tie points for image orientation and would bring color into study and presentation tasks too.

Nevertheless, photogrammetric 3D-modeling is a useful and successful tool for archaeological landscape documentation of large cultural heritage sites, even if for simple visualization, preliminary and overall understanding of the area or documentation at smaller scale, satellite imagery could also be employed (Gruen et al., 2005). Together with terrestrial range- (Blais, 2004) or image-based (Remondino and El-Hakim, 2006) techniques, good results can be achieved and combined for cultural heritage site modeling.

The achieved results show that digital models resulting from photogrammetric processing are a more realistic and competitive edge versus CAD techniques and deliver useful information to safeguard and reconstruct an historic and natural landscape as a whole.

Fig. 5 Comparison of the aerial photos used for modeling (above) and satellite data (below, from Google Earth) showing Angkor Wat, and its southwestern corner, at the right the central part of Bayon. There is a visible difference in the resolution.

Acknowledgements

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