3D Modeling of large cultural heritage sites from satellite and aerial images

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ABSTRACT

Recently, the need for preservation and documentation of cultural heritage has become more and more important throughout the world. This requires the adoption of modern and efficient techniques for data acquisition, especially for large sites. Photogrammetry and Remote Sensing are well-suited technologies for large area mapping and modeling tasks, and the derived products can serve as a data basis for archaeological prospection, 3D modeling of terrain and buildings, and regional scale GIS analyses. The high data processing speed available today, new methods of visualization and the development of information systems for spatial analysis increase the benefit of image data. A high degree of automation is a prerequisite to improve the efficiency of image-based modeling techniques in cultural heritage. New methods developed at our group, focusing on sensor modeling, automated aerial triangulation, Digital Surface Model (DSM) generation and object extraction will be addressed in this paper. The shortcomings and limits of airborne and satellite sensors and images will be critically pointed out and potential for future enhancement will be discussed. We briefly describe the current state of the available technology by means of projects conducted successfully by our group, e.g. the 3D reconstruction of the Bamiyan valley in Afghanistan, the recording of the geoglyphs of Nasca/Palpa, Peru and the 3D modeling of the pre-columbian site Xochicalco in Mexico.

INTRODUCTION

At the latest in 1972, when the general conference of the UNESCO passed the convention concerning the protection of the world cultural and natural heritage (UNESCO, 1972), the need for protection, conservation and presentation of cultural and natural heritage has become a global concern. An elementary task today is the documentation of large cultural and natural heritage sites, not only for preservation but also for scientific research and presentation purposes. Recent developments in the fields of photogrammetry, remote sensing and computer science offer new potentials in terms of data processing, analysis and visualization.

On the other hand, large site documentation and mapping can still be associated with high expenses in terms of costs, time consuming data processing procedures, and the requirement of expertise and special equipment. Photogrammetry and Remote Sensing already today provide highly efficient methodologies, well suited especially for large site mapping. Furthermore, both technologies enhance the range of derivable products compared to other data acquisition methods. Digital Surface Models (DSM), orthoimages, 2D and 3D vector data with attributes, and photorealistic 3D models as well as traditional 2D maps can be produced efficiently at a high level of accuracy and completeness. Figure 1 illustrates the digital photogrammetric workflow required for the derivation of those products. Recently, new sensors such as digital aerial cameras, high-resolution satellite sensors, laserscanners and photogrammetric software provide useful tools for data acquisition and processing accompanied with a high degree of automation. In this paper we will demonstrate that photogrammetric techniques and software systems, partially developed by our group, which have proven to be suited for a wide range of applications, also meet the requirements for 3D documentation of large cultural heritage sites. Moreover, examples of successfully conducted projects using photogrammetry and remote sensing will be given.

1. DIGITAL AERIAL CAMERAS

In recent years, various manufacturers introduced digital aerial cameras into the market, being nowadays distributed and employed as commercially available systems for aerial image acquisition. The Leica ADS-40, Starlabo's Starimager SI250, Z/I Imaging DMC, and Vexcel's UltraCam D are prominent examples. Generally, one distinguishes between two technical principles applied: linear array and matrix array sensors. While the first class makes use of one or several linear arrays of CCD elements in the focal plane, the second uses a matrix-shaped CCD sensor for image capture.

An exemplary overview of different aerial digital large format sensors is given in Table 1.

Table 1 – Overview of large format digital aerial cameras (MS = multispectral, PAN = panchromatic)

System	*Type*	*Camera Heads*	*Format*	*Pixel size*	*Radiometric Resolution (nominal)*
Z/I Imaging DMC®	Frame	4 (PAN) 4 (MS)	7680x13824 pixels composite image size (PAN) 2000x3000 pixels per head (Multispectral)	12μm	12 bit
Vexcel UltraCam D™	Frame	4 (PAN) 4 (MS)	7500x11500 pixels composite image size (PAN) 2672x4008 pixels image size (Multispectral)	9μm	12 bit
Leica ADS-40	Linear Array	6 PAN, 4 MS lines	12000 pixels per line	6.5μm	14 bit
Starlabo STARIMAGER® SI250	Linear Array	10 MS	14400 pixels per line	5μm	11 bit

Linear array sensors can be briefly described by the following characteristics: each image line must be oriented using a separate set of parameters, therefore platforms with integrated GPS/INS systems are necessary, large image formats can be achieved, n-fold stereo overlap can be obtained through integration of n different viewing directions, almost parallel projection in flight direction.
The image acquisition method applied by matrix array sensors is very similar to image acquisition using conventional film based aerial cameras. During the photo flight, an adequate image overlap in flight direction and between strips has to be ensured by the operator. Unlike for linear array imagery, one set of orientation parameters is valid for each whole image. In case of the Z/I DMC and Vexcel UltraCam D, where 4 single images are taken simultaneously according to the number of camera heads, a composite image is derived first to achieve a large format image.
The main benefit of using digital aerial cameras for photogrammetric processing compared to cameras based on analog film is the omission of the time consuming scan procedure. Due to the higher dynamic range of CCD sensors compared to analog film, CCD images contain more information especially in dark shadow and in light, almost saturated areas. There exists a problem with commercial photogrammetric software in that it currently does not support very well the new sensor models for linear array imagery. At the present state, the availability of digital aerial cameras is not always given. Therefore, in most cases existing images or photo flights using film-based cameras have to be considered.

2. SATELLITE IMAGERY

Nowadays, various operating companies of earth observation satellites offer a variety of products derived from satellite images, mainly images at different processing levels and Digital Elevation Models (DEM). The available radiometric, geometric, spectral and temporal resolutions and the area covered by a scene differ from sensor to sensor as well as the prices. Commercially available images vary between high geometric resolution (0.6 m to 5 m), medium resolution (5 m – 30 m) and low resolution (30 m – 300 m). Today, satellite platforms usually use linear array CCD sensors for image acquisition, e.g. QUICKBIRD, IKONOS and SPOT-5 (high resolution) or ASTER (medium resolution). A low priced, film based alternative is CORONA imagery, acquired between 1959 and 1972 for military purposes and made available to the public by the USGS. Table 2 shows some characteristics of satellite images acquired by different sensors.

Table 2 – Charcteristic data for selected satellite sensors

Sensor	*Operator*	*Geometric resolution*	*Stereo*	*Technology*	*Prices*
IKONOS	Space Imaging	1 m	Yes	Linear Array CCD	13-27 USD (per km^2)
QUICKBIRD	Digital Globe	0.66 m	Yes	Linear Array CCD	14 USD (per km^2)
SPOT-5	Spot Image	2.5 m	Yes	Linear Array CCD	8600 USD (60x60 km^2)
ASTER	USA (NASA)	15 m	Yes	Linear Array CCD	55 USD (60x60 km^2)
CORONA	USA	2 – 3 m (depending on the mission)	Yes	Film	24 USD (scanned image)

Investigations concerning satellite imagery done in our group, especially accuracy tests performed on georeferencing procedures, point positioning, DSM generation and orthoimage generation for QUICKBIRD and IKONOS imagery (Eisenbeiss *et al.*, 2004) and SPOT-5 images (Poli *et al.*, 2004) have shown the high potential in terms of accuracy for optical satellite sensors. For cultural heritage applications, e.g. prospection, DSM generation and mapping of large sites, satellite imagery can be a worthwile alternative to aerial images. However, it should be taken into consideration that the geometric resolution of commercially available satellite images is still far inferior compared to aerial images.

3. NEW METHODS FOR DIGITAL PHOTOGRAMMETRIC PROCESSING

Commercial photogrammetric software for digital photogrammetric processing is available since the late 1980s. Since then, a lot of effort has been invested, aiming at a higher degree of automation especially for georeferencing, aerial triangulation, DSM generation and 3D object extraction. Still, a software package which could obtain reliable and highly accurate results for all these tasks in a fully automated process is not on the market. In our group, new methods for various applications have been developed, trying to overcome shortcomings of currently available commercial software, such as new sensor models and image matching algorithms.

3.1 IMAGE ORIENTATION, TRIANGULATION (GEOREFERENCING)

One important prerequisite for accurate image orientation in photogrammetric projects is the sensor model. Various sensor models e.g. for linear array satellite images (Poli *et al.*, 2004; Zhang & Gruen, 2004) and the Starlabo TLS airborne sensor (Gruen & Zhang, 2003) were developed, implemented and tested by our group. In current commercial digital photogrammetric software, a lack of sensor models for linear array sensors can be observed. At the present state, most software developers only support their own cameras (e.g. Leica), and this only for a limited number of functions. A procedure important for image orientation is the measurement of tie points and control points. While control points have to be measured semi-automatically, tie point extraction can be widely automated by means of image matching, a process aiming for measurement of corresponding points in two or more images. The quality of the results is mainly affected by low image contrast areas (e.g. desert, forest) and other factors. Blunder detection and deletion in the point measurements are time consuming tasks, which also are not implemented in a reliable and automated mode in commercial software systems. After tie point and control point measurement, image orientations for the whole image block can be calculated by bundle adjustment. From the oriented images, in the following steps of the workflow, the above mentioned photogrammetric products can be derived (Fig. 1).

3.2 AUTOMATED DSM/DTM GENERATION

Automatic DSM/DTM generation by means of image matching nowadays is implemented in different commercial photogrammetric workstations. A wide variety of image matching algorithms exist, and although different algorithms and matching strategies are applied, the major systems encounter similar problems in terms of accuracy and reliability compared to standards set by manual measurements (Gruen *et al.*, 2000). The main problems which affect the accuracy of automatically generated DSM/DTM are described in detail in Gruen & Zhang (2002). To make use of the advantages that Linear Array imagery can provide, a new matching approach was developed and implemented in our TLS-IMS software module. The matching procedure is described in detail in Gruen & Zhang (2003). A similar approach, suited for automatic DSM generation from satellite images, was implemented in the SAT-PP (Satellite Image Precision Processing) software (Zhang & Gruen, 2004). Although accuracy tests have shown that accurate results (about 1 pixel for satellite imagery, 3-5 pixels for aerial imagery) for automated DSM generation can be achieved with both matchers, there is still room for improvement, especially in blunder detection, noise reduction and reduction from DSM to DTM. These improvements are necessary before DSMs/DTMs can be derived automatically at an equal level of accuracy compared to manually measured Digital Terrain Models, acquired on an analytical plotter. Accurate DSM/DTM data is needed as a basis data for orthophoto generation. Most commercial photogrammetric softwares allow for automated or manual generation of seamlines, which define the image areas being considered during orthophoto calculation.

3.3. OBJECT EXTRACTION

In commercially available digital photogrammetric software, object extraction functionality is limited and restricted to manual or semi-automated measurements together with the capability of attribute data acquisition. The main applications are 3D modeling of city and industrial areas. Actual commercial systems assist the human operator measuring 3D objects in combination with registration of attribute data in a semi-automated mode, e.g. Leica Photogrammetry Suite, Z/I Image Station or Virtuozo IGS Digitize. These systems provide libraries containing objects, e.g. buildings or streets, which allow for object modeling according to certain rules concerning object topology. In a second step, using suitable modeling software like e.g. CyberCity Modeler (Gruen & Wang, 2002), a textured 3D model can be produced from the input data (DTM, orthoimage, measured objects). An example using CyberCity Modeler for 3D modeling of terrain and buildings in an archaeological application was conducted for the pre-hispanic site of Xochicalco, Mexico, where an urban center was reconstructed photogrammetrically from aerial images (Fig. 2).

4. CASE STUDIES

Various successful projects have been conducted or are work in progress in our group, dealing with 3D modeling of large cultural and natural heritage sites, e.g. the Bamiyan project, 3D reconstruction of the Nasca/Palpa geoglyphs in Peru, 3D modeling of Mount Everest (Gruen & Murai, 2002) and the 3D reconstruction of adobe architecture at Tùcume, Peru (Sauerbier *et al.*, 2004), Machu Picchu and others. In this context, two of these projects will be briefly presented to demonstrate the variety of requirements and products for different applications, which can be derived with photogrammetric methods from aerial and satellite imagery.

4.1. THE BAMIYAN PROJECT

The Bamiyan region, situated about 200 km north-west of Kabul in Afghanistan, is one of the most famous Buddhist monument sites worldwide. Global attention was attracted to Bamiyan since the Taleban regime destroyed the standing statues in 2001. In the following years, photogrammetric processing was used at our Institute for different purposes: 3D reconstruction of the statues and 3D reconstruction of the rock façade (Gruen *et al.*, 2002), both from terrestrial close-range images, generation of a high resolution mosaic of the fresco in the Great Buddha's niche (Remondino & Niederoest, 2004) and a digital terrain model of the Bamiyan valley and its surroundings generated from SPOT-5 and IKONOS satellite imagery using SAT-PP (Poli *et al.*, 2004).
The empty niches of the Buddha statues can clearly be seen in the 3D view generated from the textured 3D model derived from SPOT-5 and IKONOS imagery using the SAT-PP software system (Fig. 3). In the future, an integration of the different mutli-resolution datasets into one 3D model using visualization software with realtime navigation capability would be desirable. There is still no software system on the market, which would meet the requirements of multi-resolution, realtime visualization of real 3D data. Another aim of the project is the development of a tourist information system for the Bamiyan region in the near future (Gruen *et al.*, 2005).

4.2. THE NASCA/PALPA PROJECT

In this project, analog aerial images were processed with the goal to extend archaeological research by means of modern technologies such as photogrammetry and GIS (Reindel & Gruen, 2005). Our goal is a 3D reconstruction and GIS-based management and analysis of the ground drawings in the Nasca region, located about 400 km south-east of Lima in Peru. The geoglyphs have been carved into the ground during the period from 200 BC to 650 AD by the ancient Nasca. In 1997/98, two photoflights were conducted using an analog aerial camera Zeiss RMK 15/23 to acquire images (B/W and colour) at a scale of 1:7000 covering the region around the modern town of Palpa. After aerotriangulation and bundle adjustment, 379 images were oriented, covering an area of about 89 km^2. Various products were derived, most of them by manual measurement: A high resolution DTM (2 m mesh size), an orthomosaic with a footprint of 0.28 m, 3D vector data from geoglyph mapping and topographic objects, resulting in the first complete map available for geoglyph documentation in the Palpa region (Lambers, 2004). The DTM was measured manually on an analytical plotter after accuracy tests had shown that an automated approach did not yield sufficient results (Gruen *et al.*, 2000). A 3D model textured with the orthomosaic and the geoglyph layer was produced and visualized using different visualization software packages (Sauerbier & Lambers, 2003) (Fig. 4).
Together with archaeological attribute data acquired during several campaigns of field work, the data was integrated into a spatial database according to a specially designed data model (Lambers & Sauerbier, 2003) to enable an efficient GIS-based management and analysis of both archaeological and spatial data. Altogether, about 3 GB of spatial data (DTM, orthomosaic, vector data) and 10 MB of archaeological data were generated and stored in the database.

CONCLUSIONS

Recently, the growing acceptance and increased applications of new technologies in the cultural heritage community, especially in the GIS sector, caused a greater demand for spatial data also for large site mapping and 3D modeling purposes. High accuracy is a prerequisite for a wider acceptance of photogrammetry and remote sensing as valuable means for efficient data acquisition, be it for DSM/DTM, orthoimage or vector data generation. We have shown some of the latest developments in the area of digital aerial sensors, which will play an important role in aerial image acquisition in the future, and spaceborne sensors, where commercial products of very high resolution imagery are available. Generally, CCD sensors will contribute to increase the efficiency of photogrammetric image processing notably as the time consuming procedure of image scanning will be spared. Some of the latest developments in terms of photogrammetric processing software have been described considering as example our inhouse software modules SAT-PP and TLS-IMS. Nevertheless, aiming at full automation of the photogrammetric processing procedures, still a big effort in terms of further research and development is required. Fully automated aerial triangulation and DSM generation at high accuracy and robustness have still some potential for improvement and are not yet available in commercial software in sufficient quality. Object extraction currently is conducted in manual or semi-automated mode, since full automation of this procedure cannot be expected in the near future. Furthermore, three projects, conducted successfully by application of photogrammetric and remote sensing techniques, showed the wide range of possible applications of photogrammetry and remote sensing in large cultural and natural heritage site mapping and modeling.

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FIGURES

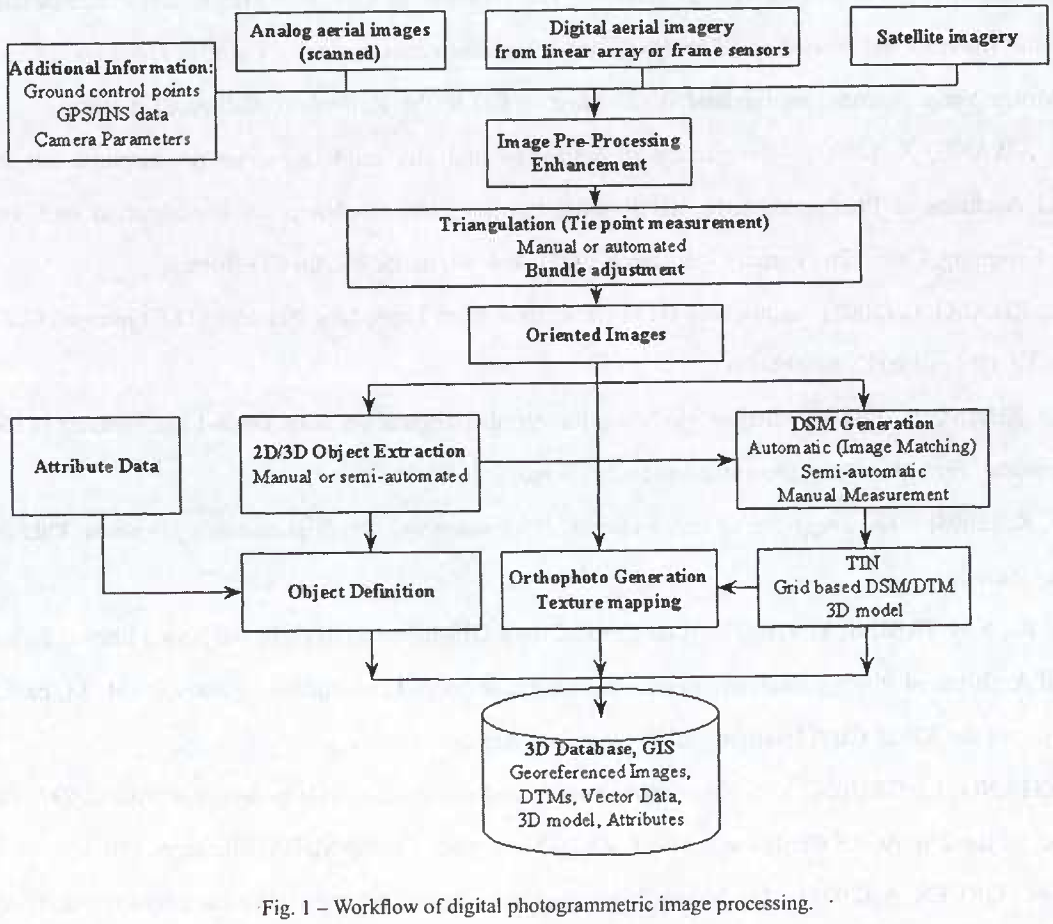

Fig. 1 – Workflow of digital photogrammetric image processing.

Fig. 2 – 3D view onto the textured 3D model produced by CyberCity Modeler. Visualization by ERDAS VirtualGIS.

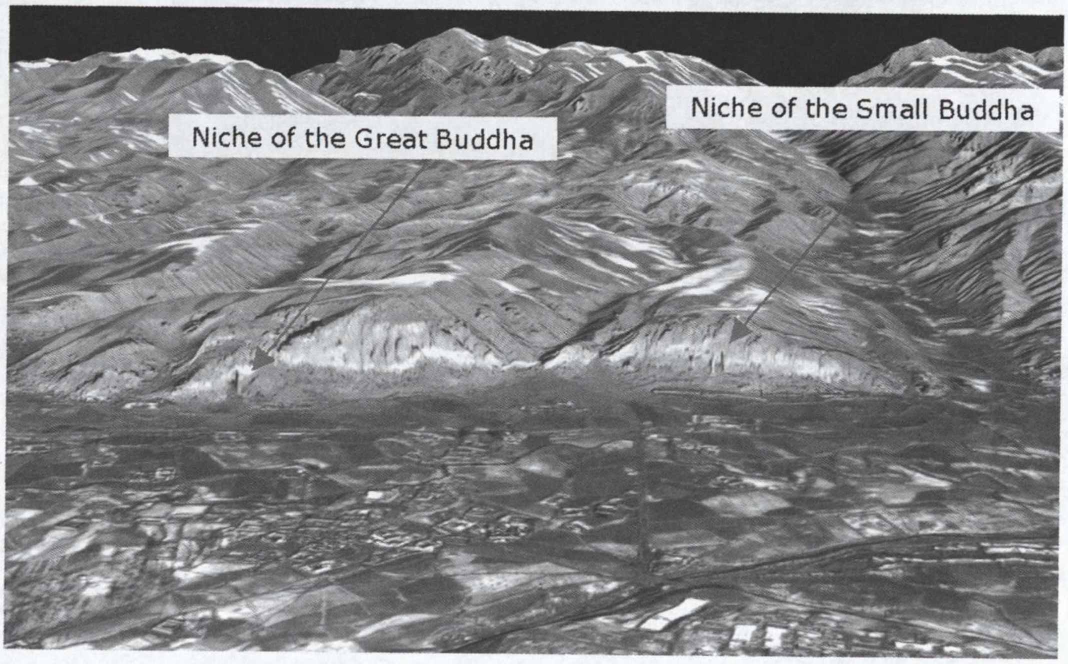

Fig. 3 – View onto the 3D model textured with the IKONOS orthoimage in direction of the rock cliff façade containing the empty niches of the Buddhas.

Fig. 4 – 3D view of a geoglyph complex at Sacramento (Palpa), produced from the textured DTM overlaid with the geoglyph layer.