NEW TECHNOLOGIES FOR EFFICENT LARGE SITE MODELING

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ABSTRACT:
The recording and 3D modeling of large Cultural Heritage sites is currently receiving much attention. This has two main reasons. On the one hand UNESCO pays more attention to large cultural and natural sites and on the other hand we have a wide array of new technologies available which greatly support the efficient generation, administration and analysis of such models. Data from high-resolution satellite sensors and digital large format aerial cameras are increasingly becoming available. The same applies to laser scanners, digital panoramic and still video cameras. Also, the automation of photogrammetric processing has made some progress recently, in particular through the development of better matchers for relative orientation, tie point measurement in triangulation and surface model generation and the introduction of semi-automated procedures for ground control point measurement and feature/object extraction. In addition, Spatial Information System technology provides many functions of interest for data administration and analysis. Finally, also visualization and animation software is becoming affordable at better functionality and lower costs. So the time is ready to use these devices more extensively in Cultural Heritage recording, modeling and visualization.
This paper, after a brief review of the currently available high-resolution satellite images and the new large format digital aerial cameras, addresses the issue of automated processing and describes our software system for the 3D processing of Linear Array imagery. Of particular interest for archaeological and cultural heritage applications is the new concept of UAV-based data acquisition. We present here the successful use of a model helicopter in Pinchango Alto, Peru. Among the projects which we conducted recently we address here briefly Túcume, Peru and Bamiyan, Afghanistan.

KEYWORDS: Modeling, Visualization, Documentation, Cultural Heritage, Sensor

1. INTRODUCTION

The modeling of large sites has received much attention in recent years. This was triggered on the one side by the increased interest of UNESCO and other supranational and national organizations and on the other side by the new technologies available for recording, processing, administration and visualization of the data. As can be see from the UNESCO World Heritage List (whc.unesco.org), many recent additions can actually be classified as „Large Sites“, both in terms of culture and nature. In a press release (No. 2002-77: *„For UNESCO, Space Technologies should be Harnessed for Sustainable Development“)* UNESCO has stressed the use of satellite imagery for monitoring World Heritage sites. Lately many conferences are devoted to this issue (e.g. the International Symposium on „Conserving Cultural and Biological Diversity: The Role of Scared Natural Sites and Cultural Landscapes“, 30 May – 2 June in Aichi, Japan, on occasion of the World Exhibition 2005). Conservation and management of these sites rely heavy on the availability and timeliness of data.
On the technology side we have nowadays at our disposal a vast array of relevant and efficient data acquisition tools: High-resolution satellite images, large format digital aerial cameras, hyperspectral sensors with several hundreds of channels, interferometric radar from space and aerial platforms, lasers canners of aerial and terrestrial type, partially with integrated cameras, model helicopters with off-the-shelf digital cameras, panoramic cameras and a large number of diverse customer still video cameras and camcorders. This is augmented by GPS/INS systems for precise navigation and positioning.
Automated and semi-automated algorithms allow us to process the data more efficiently than ever before and Spatial Information System technology provides for data administration, analysis and other functions of interest. Finally, also visualization and animation software is becoming affordable at better functionality and lower costs. This sets the scene for a totally new evaluation of the tools and techniques for large sites cultural heritage recording and modeling.
We have conducted in the past a number of projects that have shown the potential, but also the limitations of some of these new technologies. Among those are (see also http:\\www.photogrammetry.ethz.ch under PROJECTS): Mount Everest, Ayers Rock/Australia, Kunming/China, Bamiyan/Afghanistan, Geoglyphs of Nasca/Peru, Tucume/Peru, Inka settlement Pinchango/Peru, Machu Picchu/Peru (in work), Xochicalco/Mexico.
In this paper we will report about our experiences with large site modeling and also address some of the new algorithmic approaches and software modules for the 3D processing of digital satellite and aerial images that we have developed in the course of these projects. Here we will limit ourselves to a brief description of the Bamiyan and Tucume projects.

2. PHOTOGRAMMETRY AND REMOTE SENSING

Photogrammetry and remote sensing are image-based techniques for the extraction of metric and semantic information from images. Originally terrestrial photogrammetry, aerial photogrammetry and satellite remote sensing developed along separate lines, both in terms of types of sensors used and processing methodology and tools. Today, within an almost totally digital environment, we see a strong trend towards convergence. This opens the path for a much more cost-efficient use of a variety of different sensor data and processing tools.
We will concentrate in this paper on the processing of satellite and aerial images, because they are most relevant when it comes to large site modeling. Figure 1 shows the workflow of the photogrammetric techniques used to turn images into hybrid 3D models („hybrid“ meaning mixed models including geometry and texture).

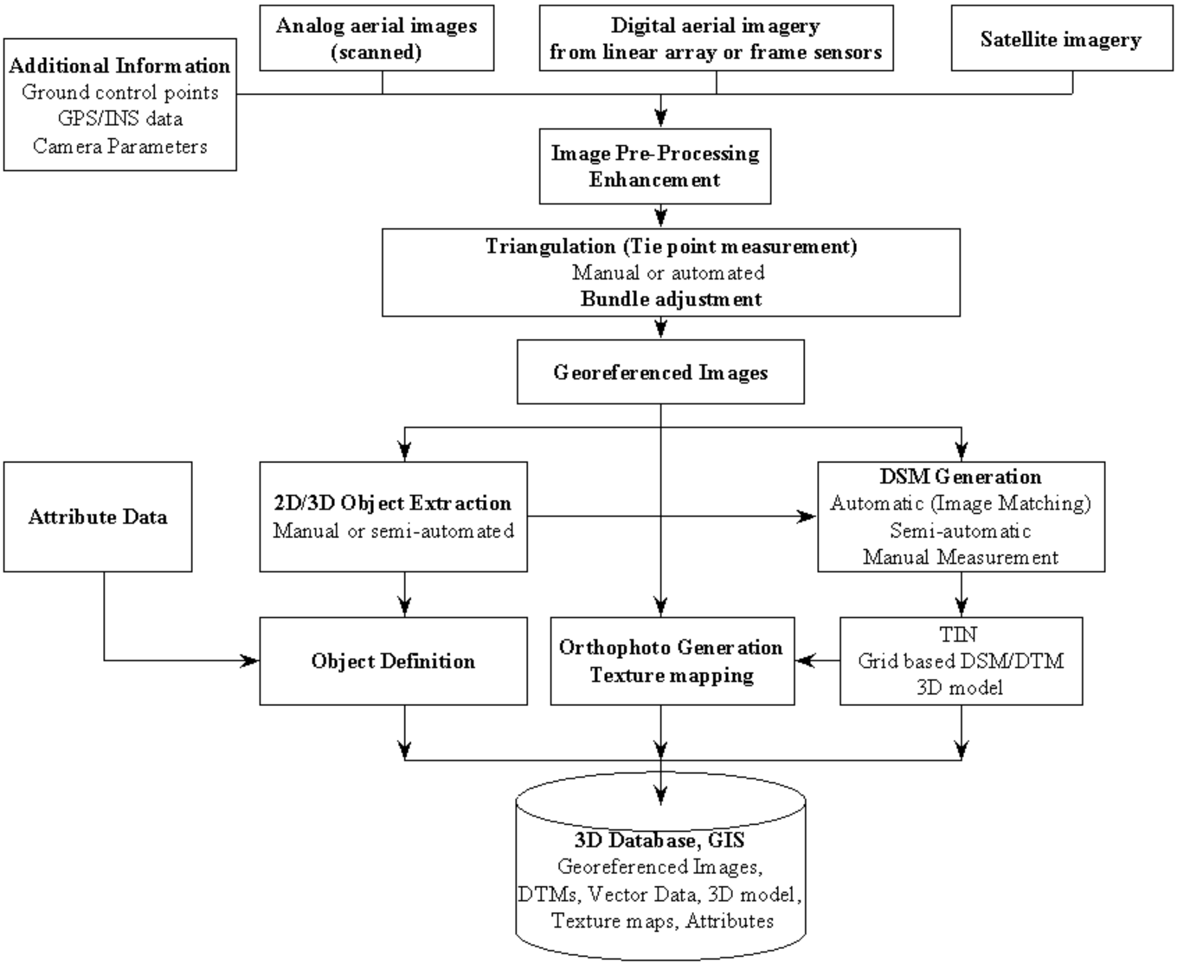

Figure 1: Workflow and products of the photogrammetric/remote sensing process.

3. RELEVANT SATELLITE SENSORS AND NEW AERIAL DIGITAL CAMERAS

The development and increased availability of high-resolution, multispectral and stereo-capable satellite sensors and of a new generation of digital large format aerial cameras is very crucial for the efficient modeling of large sites. Table 1 shows an overview of high-resolution satellite sensors (including medium resolution ASTER because of its good availability and low costs), which might be useful in cultural heritage applications. There is a great variety of image products available in terms of geometrical resolution (footprint), spectral resolution (number of spectral channels) and costs. All images of Table 1 are acquired with digital sensors, using Linear Array CCD camera technology. For precise processing this requires a particular sensor model and the related special software (see chapter 4). There are and have been also a number of film-based photographic satellite cameras in use (Jacobsen et al., 1999). This includes the US Corona satellite (2-3 m footprint, B/W, stereo, US$ 24 for a scanned image). The availability of images and the costs can be checked through a number of image providers over the Internet (see Table 1). It is very important to select the right product for a particular task.

We are witnessing right now a move of photogrammetry towards the use of large format digital aerial cameras. A number of manufacturers are offering their products since 2000 and these cameras have found their way already to many customers. Table 2 gives an overview of the current status in digital aerial large format camera development. We define „large format“ as having more than 10 000 pixels in one image format direction. There are many consumer-type still video cameras on the market, some of them with up to 16 Mpixel image format, but non of them will even closely match the format of these professional cameras.

4. NEW METHODS FOR DIGITAL PHOTOGRAMMETRIC PROCESSING

The new generation of sensors have a number of particular properties which require new approaches in processing, if the inherent accuracy potential shall be used. Images from CCD sensors do have a much larger dynamic range than film-based images, so there is more detailed radiometric information present in those images. This is important in particular in areas of shadows and areas close to saturation. Linear Array sensor do have almost parallel projection in flight direction, which leads to less occlusions and gives better orthoimage products. Linear Array imagery, if acquired in multi-image mode, e.g. by Three-Line-Scanners or Multi-Line-Scanners, has 100% overlap for all strip images over the same area. This delivers better precision and reliability of results. Finally, Linear Array imaging systems are using GPS/INS sensors for position and attitude determination of the imaging sensor, which can be used advantageously at different stages of the processing chain.

Taking into consideration these facts and other parameters and constraints, we have developed some new methods and the related software packages for the high accuracy processing of aerial and satellite Linear Array images.

Table 1: Main characteristics of high and medium resolution pushbroom sensors carried on satellites.
L = along-track; C = across-track, PAN = panchromatic, MS = multispectral

Sensor	**Numb. cameras**	**Focal length (mm)**	**Stereo**	**Incidence angles (°)**	**Channels**	**Ground resolution (m)**	**Swath width (km)**	**Numb. pixels/line**	**Image providers**
QUICKBIRD	1	8800	L[1]	up to ±30	PAN RGB, NIR	0.6 2.4	16	27000	Digitalglobe http://www.digitalglobe.com
IKONOS-2	1	10000	L[1]	up to ±60	PAN RGB, NIR	1 4	11	13500	Spaceimaging http://www.spaceimaging.com
ORBVIEW-3	1	2820	L[1]	up to ±45	PAN RGB, NIR	1 4	8	8000	Orbimage http://www.orbimage.com
EROS-A1	1	3500	L/C[1]	up to ±45	PAN	1.8	14	7800	ImageSat Int. http://www.imagesatintl.com
ALOS-PRISM	3	2000	L	0 ±24	PAN	2.5	70 35	28000 14000	TBD
SPOT-5/HRG	2	1082	C	up to ±27	PAN RG, NIR	5 (2.5) [2] 10	60	24000 6000	SpotImage http://www.spotimage.com
SPOT-5/HRS	2	580	L	±20	PAN	10	120	12000	Spotimage http://www.spotimage.com
ASTER-VNIR	2	329	L	0 0, -27	RG NIR	15	60	5000	LP DAAC (NASA) http://edcimswww.cr.usgs.gov/pub/imswelcome/

For the aerial case we have developed a complete software system in cooperation with Starlabo Inc., Tokyo, the manufacturer of the Three-Line Scanner STARIMGER, consisting of the different modules (Table 3).

For the satellite image case we have developed a modified version of this software, called **SAT-PP** (**Sat**ellite Image **P**recision **P**rocessing), with similar functionality as described before. The key difference to the aerial case is the use of other sensor and trajectory models.

In recent years we have done a number of experiments and tests with TLS/STARIMAGER aerial images (Gruen and Zhang, 2003a, Zhang and Gruen, 2004) and with satellite stereo images from SPOT (Poli et al., 2004), IKONOS and Quickbird (Gruen and Zhang, 2003b, Eisenbeis et al., 2004, Gruen, et al., 2005) with respect to georeferencing (orientation), measurement accuracy (point positioning), Digital Surface Model (DSM) determination and orthoimage generation. These investigations have shown that with the proper methodology and software one can achieve extraordinary results. Both with aerial and satellite images one can get a georeferencing accuracy of better than 1

[1] one-lens sensor with ability to rotate up to a certain off-nadir angle
[2] supermode

Table 2: Large format digital aerial cameras (MS = Multispectral, PAN = Panchromatic

System	**Sensor Type**	**No. frames/ lines**	**Spectral Bands**	**Format**	**Pixel size (μm)**	**Nominal Radiometric Res. (bit)**
Z/I Imaging DMC®	Frame	4 PAN 4 MS	RGB, NIR	7680x13824 pixel composite (PAN) 2000x3000 pixel per head (MS)	12	12
Vexcel UltraCam D™	Frame	4 PAN 4 MS	RGB, NIR	7500x11500 pi composite (PAN) 2672x4008 pi (MS)	9	12
Leica ADS-40	Linear array	6 PAN 4 MS	RGB, NIR	12000 pixel per line	6.5	14
Starlabo STARIMAGER® SI250	Linear array	10 MS	RGB, NIR	14400 pixel per line	5	11
Wehrli 3-DAS-1	Linear array	9 PAN	RGB	8023 pixel per line	9	14

pixel. In automated DSM generation one can achieve a height accuracy of 1 to 5 pixels, depending one many factors like surface roughness (flat and smooth or mountainous areas), land use parameters (forest, desert, urban areas), local texture (sand, snow), time and month of image taking, etc.
Accurate DSM/DTM data is not only an important product in its own right but is also necessary for the derivation of good quality orthoimages.

Table 3: TLS modules for aerial linear sensor

TLS-SMS	• User interface • Image measurement in mono and stereo • 3-ray forward intersection (point positioning) • Image and shadow enhancement
TLS-IRS	• Quasi-epipolar rectification to plane or via DTM/DSM • Orthoimage generation
TLS-LAB	• Sensor/trajectory modeling, • georeferencing/triangulation • Automatic and semi-automatic tie points generation
TLS-IMS	• Image matching for DSM/DTM generation • DSM/DTM modeling and interpolation
CC-Modeler **CC-TLSAutotext**	• Feature/object extraction (e.g. city modeling)

5. STATUS OF AUTOMATED PROCESSING

The automation of photogrammetric processing is obviously an important factor when it comes to efficiency and costs of data processing. The success of automation in image analysis depends on many factors and is a hot topic in research. Progress is slow and the acceptance of results depends on the quality specifications of the user. Also, the image scale plays an important role in automation. Potentially, the smaller the scale the more successful automation will be. Therefore it is a bit difficult to make firm statements which would be valid in all cases. However, in general one can state that
- orientation and georeferencing can be done in parts automatically
- DSM generation can be done automatically, but may need substantial post-editing
- orthoimage generation is a fully automatic process
- object extraction and modeling is possible in a semi-automated mode at best

Since object extraction and modeling constitute very important elements in cultural heritage applications we will give some specific comments on that in the following.

5.1 Object extraction and modeling

In commercially available digital photogrammetric software, object extraction functionality is 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. Commercial systems assist the human operator in 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. However, there is no functionality available that would consider the specific requirements of cultural heritage modeling.
For the 3D modeling of buildings and other man-made objects we have developed and tested a methodology called CyberCity Modeler (CC-Modeler). This is a semi-automated technique, where the operator measures manually in the stereo-model a weakly structured point cloud, which describes the key points of an object. The software then turns this point cloud automatically into a structured 3D model, which is compatible with CAD, visualization and GIS software. Texture can be added to the geometry to generate a hybrid model. A DTM can also be integrated. 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 (Figure 2), where an urban center was reconstructed photogrammetrically from aerial images (Gruen and Wang, 2002).

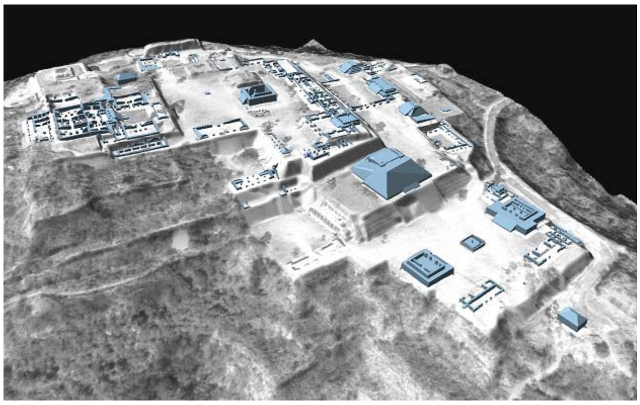

Figure 2: Partially textured 3D model of Xochicalco, derived semi-automatically from a stereo pair of aerial images using CyberCity Modeler

6. A REMOTELY CONTROLLED MODEL HELICOPTER OVER PINCHANGO ALTO, PERU

Model helicopters belong to the class of UAVs (Unmanned Aerial Vehicles). These vehicles are used in a great variety of applications. Lately we have applied such a system to Cultural Heritage modeling.
In the vicinity of Palpa, the pre-hispanic site of Pinchango Alto is an attractive, yet difficult target for archaeological research. On the one hand, its stone architecture, abundant surface finds, and richly furnished graves dating to the Late Intermediate Period (AD 1000-1400) offer many opportunities to study this still poorly understood pre-Inkaic period. On the other hand, access to and working on the site is rather difficult. The recording of the preserved surface remains therefore requires a highly mobile and flexible documentation system. In a 2004 field campaign we used a model helicopter carrying a CMOS camera to acquire a series of vertical aerial images for photogrammetric recording and 3D modeling of the site and the surrounding terrain. The system used in Pinchango Alto is based on a commercial low cost model helicopter (Figure 3). It features an integrated GPS/INS based stabilizer. While the GPS/INS unit enables semi-automated navigation along a predefined flight path, the stabilizer ensures a stable flight attitude and thus highly reliable image acquisition. The processing and analysis of the acquired images encompassed image pre-processing, semi-automatic triangulation and automated DTM generation. A 3D model of the site was produced and visualized (Figure 4). The results were analyzed concerning in particular the potential of DSM generation from

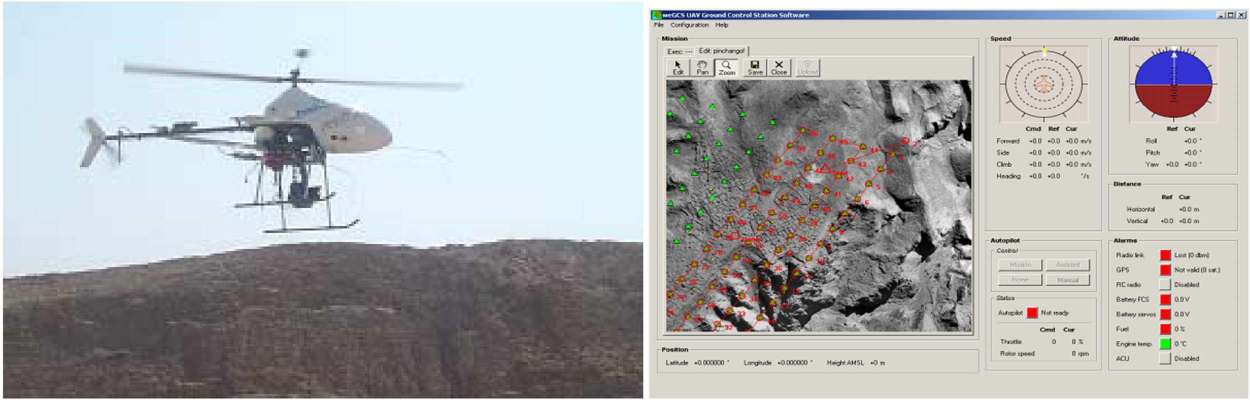

Figure 3: Model helicopter over Pinchango Alto (left). User interface showing the flight plan and the control panel (right).

Figure 4: Pinchango Alto (marked with red box) in an aerial image of 1997 (1:7000) (left image). Snapshot of a virtual flight over the hybrid model, generated automatically from helicopter images (right).

model helicopter images as compared to terrestrial laserscan data. For details of the whole mission (data acquisition and processing) see Eisenbeiss et al., 2005.

7. FURTHER EXAMPLES

In recent years we have modeled a number of large Cultural Heritage sites, e.g. Mount Everest (Gruen and Murai, 2002), Ayers Rock/Australia, Xochicalco/Mexico (Gruen and Wang, 2002), Geoglyphs of Nasca/Peru (Lambers and Gruen, 2003, Lambers and Sauerbier, 2003, Lambers et al., 2004), Pinchango/Peru (see previous section and Eisenbeiss et al., 2005). Currently we work on Machu Picchu/Peru. For more details concerning our projects see http:\\www.photogrammetry.ethz.ch under PROJECTS. In the following we will report about the results and experiences gained with the projects Túcume/Peru (Sauerbier et al., 2004) and Bamiyan/Afghanistan (Gruen et al., 2004a,b, 2005).

7.1 3D reconstruction of adobe architecture at Túcume, Peru

In the region of Túcume in northern Peru, nearby the cities of Chiclayo and Trujillo, the so-called "Pyramids of Túcume" represent a unique example of adobe architecture built during different periods of pre-hispanic cultures. About 3000 years ago, people started to construct various buildings until they were completed during the 13th century A.D. in the period of Sicán, and later also used by the Incas. From the *Cerro La Raya*, a characteristic hill in the centre of the site, 26 adobe buildings are visible, the largest one, *Huaca Larga*, with a length of 545m, 110m in width and 21m in height. On top of *Huaca Larga*, the Incas constructed a stone building. During excavations in the last years, tombs, reliefs and coloured wall drawings were found. Besides the pyramids, the complex contains platforms, citadels, residential areas and cemeteries. The fact that Túcume has been an urban settlement area for the cultures of Lambayeque, Chimú and Inca consecutively makes it one of the most important Cultural Heritage sites of the ancient Peru.

The archaeological investigations of the adobe buildings are completed until now. As the adobe structures are heavily affected by wind erosion, the architecture should be modelled as well as possible in an unaffected state. For this reason, aerial imagery from the years 1949 and 1983 were acquired from the Peruvian SAN (Servicio Aerofotográfico Nacional, Lima), which show the adobe complex in two different states. As no control points existed for the 1949 images, two maps and the 1983 imagery had to be used for the orientation. The orientation of the 1983 images was accomplished on an analytical plotter WILD S9, while for the orientation of the 1949 images both, the analytical plotter and a digital photogrammetric workstation Virtuozo 3.1, were used. The photogrammetric products derived from the oriented 1949 images are a manually measured DTM, an automatically generated DSM, an orthomosaic and a photorealistic 3D model. For details see Sauerbier et al., 2004. The hybrid model was visualized with the software packages Skyline Terra Builder / Explorer Pro and ERDAS Imagine Virtual GIS (see Figure 5). The 3D model now can serve archaeologists and other scientists as a means for documentation, analysis and presentation of the Cultural Heritage site of Túcume in a state of preservation as of 1949.

7.2 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 big standing Buddha statues in March 2001. In the following years, photogrammetric processing was used at our group for different purposes: 3D reconstruction of the Great Buddha statue (Gruen et al., 2004a), 3D modelling of the rock façade (Gruen et al., 2005), and generation of a high-resolution mosaic of the destroyed fresco in the Great Buddha's niche (Remondino and Niederoest, 2004), all from terrestrial close-range images (old metric photographs, Internet images, semi-metric images, still video images and small format tourist images), and the generation of a Digital Terrain Model of the Bamiyan valley and its surroundings from SPOT-5 and IKONOS satellite imagery using SAT-PP (Gruen et al., 2004b).
The DTM was generated automatically from SPOT-5 stereo images for an area of 49x38 sqkm, For texture mapping we used one of the SPOT-5 images, but also an IKONOS mosaic for a smaller area of 13x20 sqkm, containing the rock façade, the village of Bamiyan and its surroundings.
The empty niches of the Buddha statues can clearly be seen in the 3D view generated from the IKONOS textured 3D model derived from SPOT-5 stereo imagery using the SAT-PP software system (Figure 6). In the future, an integration of the different multi-resolution datasets into one 3D model using visualization software with real-time navigation capability would be desirable. There is still no software system on the market, which would meet the requirements of multi-resolution, real-time 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).

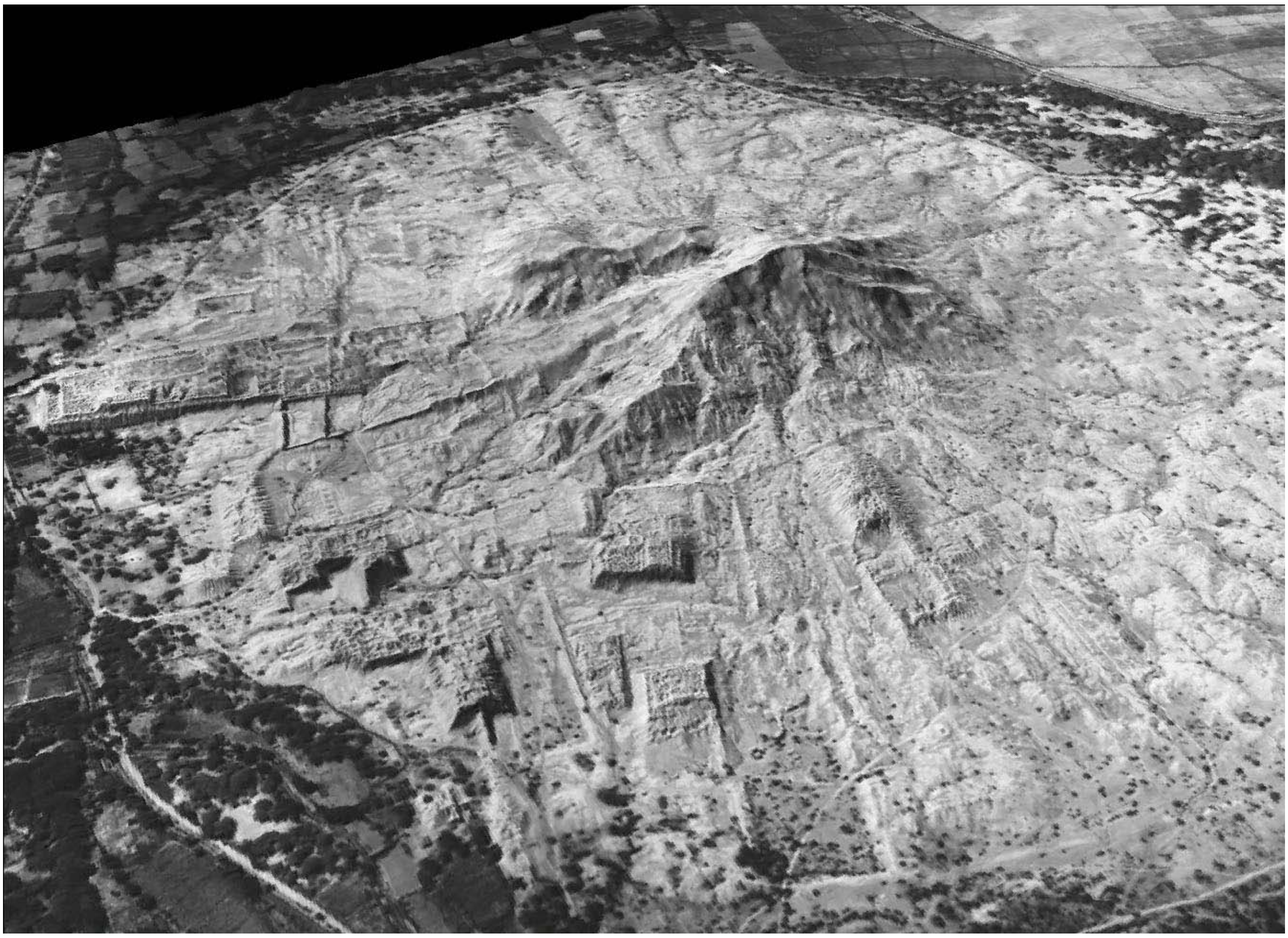

Figure 5: View onto the 3D model of the Túcume adobe complex, produced with Skyline Terra Explorer Pro. Overlaid is the texture from the 1949 aerial images. To the left is Huaca Larga, a huge adobe building of 545 m length, with an Inka stone building on top.

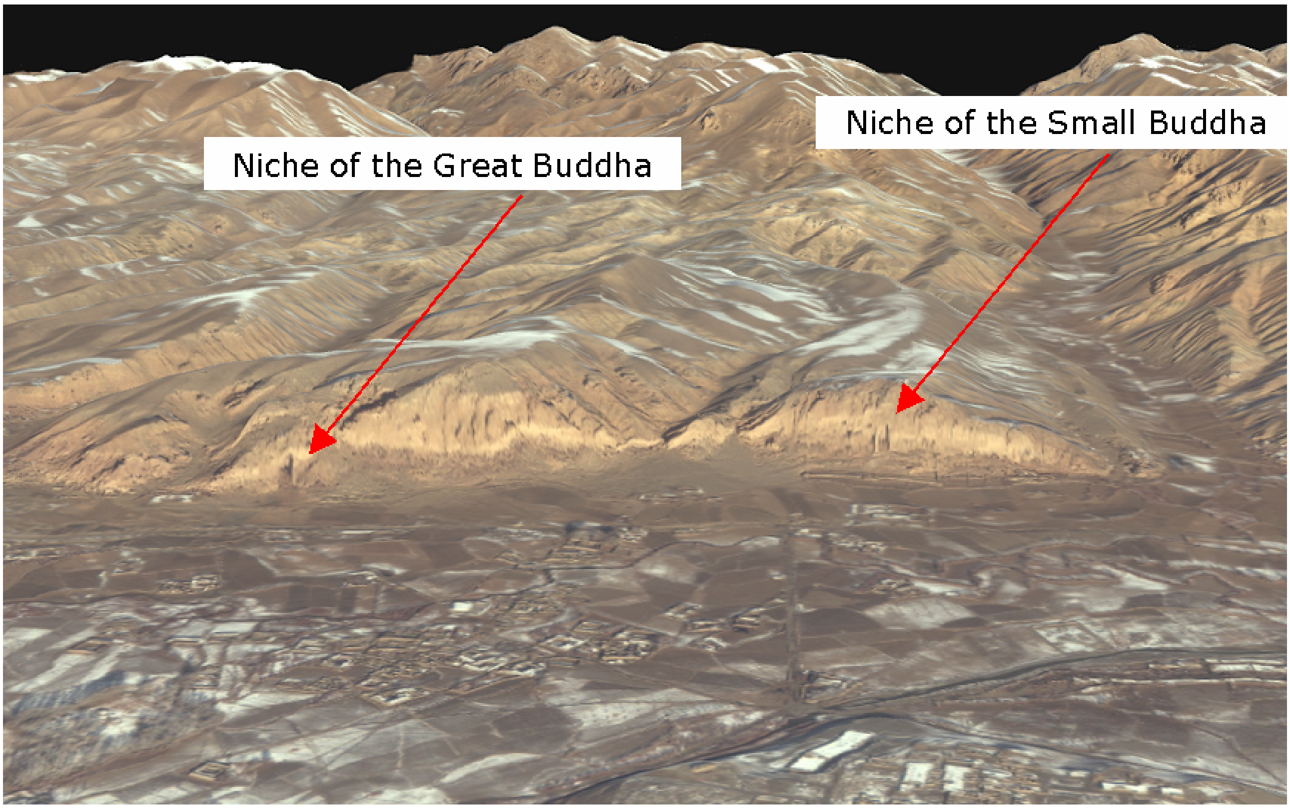

Figure 6: View onto the 3D hybrid model, textured with an IKONOS orthoimage mosaic, showing the rock cliff of Bamiyan with the now empty niches of the Buddhas.

8. CONCLUSIONS

We have shown here how high-resolution satellite images, aerial and terrestrial images can be used in order to generate hybrid 3D models for archaeological and Cultural Heritage applications with photogrammetric techniques. The digital nature of many of those images and the progress in automatic photogrammetric processing allows for very efficient procedures and for new kinds of results. Additional options for recording and processing are available through the use of aerial and terrestrial laser scanners, panoramic cameras and combined systems. Of particular interest is a UAV (**U**nmanned **A**erial **V**ehicle) - a model helicopter, which works in an autonomous mode, based on integrated GPS/INS, stabilizer platform and digital cameras, and which can be used to get images from otherwise hardly accessible areas. This system, together with advanced software for automated processing will allow us in the near future to generate at least an initial model of the object fully automatically on-line in the field or immediately after data collection in the campaign office.
All these presented technologies, together with Spatial Information Systems, 3D modeling, visualization and animation software are still in a dynamic state of development, with even better application prospects for the near future.

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