COMPUTER RECONSTRUCTION AND MODELING OF THE GREAT BUDDHA STATUE IN BAMIYAN, AFGHANISTAN

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ABSTRACT:

In the valley of Bamiyan, Afghanistan, almost 2000 years ago, two big standing Buddha statues were carved out of the sedimentary rock of the region. They were 53 and 35 meters high and the Great one figured as the tallest representations of a standing Buddha. In March 2001 the Taleban militia demolished the colossal statues, as they were considered an insult to Islam. After the destruction, a consortium was established to rebuild the Great Buddha of Bamiyan at original shape, size and place. We performed the computer reconstruction of the statue, which can serve as basis for the physical reconstruction. In this paper we report the results of our photogrammetric work on the Great Buddha of Bamiyan.

KEYWORDS: Cultural Heritage, Close Range Photogrammetry, Orientation, Matching, Reconstruction, Modeling, Visualization

1. INTRODUCTION

The region of Bamiyan, ca 200 km North-West of Kabul, Afghanistan, was one of the major Buddhist centres from the second century AD up to the time that Islam entered the area in the ninth century. For centuries, Bamiyan lay at the heart of the famous Silk Road, offering rest to caravans carrying goods across the area between China and Western Empires. Strategically situated in a central location for travellers from North to South and East to West, the village of Bamiyan was a common meeting place for many ancient cultures. In the Bamiyan valley, at 2500 meters altitude, three big statues of Buddha and a series of caves were carved out from the sedimentary rock of the region. The Emperor Kanishka ordered the construction of the statues around the second century AD. Some descendants of Greek artists who went to Afghanistan with Alexander the Great started the construction that lasted till the fourth century AD. There were two big standing Buddha, which stood about one kilometre apart, while in the center there was a smaller image of a seated Buddha (Figure 1).

Figure 1: The three Buddha statues of Bamiyan.

The larger statue (Figure 1, left) was 53 meters high while the smaller standing Buddha (Figure 1, right) measured 35 m. The Great Buddha represents Vairocana, the "Light Shining throughout the Universe" Buddha, while the small one represents Shakyamuni. They were cut from the sandstone cliffs and they were covered with a mud and straw mixture to model the expression of the face, the hands and the folds of the robe. To generate these folds of the dress, cords were draped down onto the body and were attached with wooden pegs (see Figure 7). The lower parts of their arms were constructed on wooden armatures while the upper parts of the faces were made as wooden masks. The two giants were painted in gold and other colors and they were decorated with dazzling ornaments. They are considered the first series of colossal cult images in Buddhist art. In China, India and Thailand are present many other great representations of the Buddha, as in Leshan, South-West China, where there is the world's largest statue of a seated Buddha carved in rock: it measures 71 meters in height and 28 meters in width.

The statues of Bamiyan were demolished in March 2001 by the Taleban, using mortars, dynamite, anti-aircraft weapons and rockets (Figure 2). The Buddhists, the world community, ONU and UNESCO failed to convince the Taleban to leave such works of cultural heritage. The fundamentalist Islamic militia, which has governed most of Afghanistan from 1996 to December 2001, followed an edict of its supreme leader who ordered a campaign of destruction to rid the land of all non-Islamic graven images. The Taleban refused also an offer to build a big wall in front of the statues to cover them and they blasted into dust the two giants. For the Afghanistan militia "... the Buddhas violate the Islamic prohibition against sacred images. They are false idols that must be destroyed. The statues should be destroyed so that they are not worshipped now or in the future ...".

Figure 2: The explosion of the big statue (left) and the empty cave left after the destruction (right).

After the destruction, a consortium was established with the goal of rebuilding the Great Buddha of Bamiyan at original shape, size and place. This initiative is led by the Internet-based organization *New7Wonders Foundation*, with its founder Bernard Weber and the *Afghanistan Institute & Museum*, Bubendorf, Switzerland, with its director Paul Bucherer. Our group has volunteered to perform the required computer reconstruction, which could serve as a basis for the physical reconstruction. Using our data, a first model (1:200) has already been created while a statue at 1/10 of the original size should be built and displayed in the Afghanistan Museum in Switzerland. Then this model will be used to study materials and construction techniques to be applied for the final reconstruction at full size.

Originally our interest in the computer reconstruction of the Great Buddha was a purely scientific one. We planned to investigate if such an object could be reconstructed fully automatically using just amateur images taken from the Internet with photogrammetric methods [Gruen et al., 2002]. In this case the main scientific challenge lies in the facts that no typical photogrammetric information (as interior and exterior orientation parameters) about these images is available and that existing automated image analysis techniques will most probably fail under the given circumstances. After learning about the efforts to actually rebuild the Great Buddha we decided to get involved in that project beyond a purely scientific approach and to contribute as much as we could with our technology to the success of the work. We generated different versions of the Buddha, depending on which algorithms and images were used: Internet, tourist and metric images [Gruen et al., 2003]. The results extracted from the Internet and tourist images served only for scientific purposes. The physical reconstruction should be based on a 3D computer model derived from the three metric images. These photographs were acquired in Bamiyan in 1970 by Prof. Kostka, Technical University of Graz [Kostka, 1974]. They form the basis for a very precise, reliable and detailed reconstruction with an accuracy of 1-2 cm in relative position and with an object resolution of about 5 cm. In order to achieve these values we had to apply manual image measurements, as the automatic procedures could not extract all the fine details.

In this paper we only present the results of the computer reconstruction obtained with the three metric images. For a more detailed technical description of the digital photogrammetric procedures on all the data sets, we refer to [Gruen et al., 2002, 2003].

2. THE METRIC IMAGES

The metric images were acquired with a TAF camera [Finsterwalder et al., 1968], a photo-theodolit camera that acquires photos on 13x18 cm glass plates. The original photos were scanned by Vexcel Imaging Inc with the ULTRA SCAN 5000 at a resolution of 10 micron. The final digitized images resulted in 16930 x 12700 pixels each (Figure 3). Their acquisition procedure (Figure 4, left) is known as well as the interior parameters of the camera [Kostka, 1974].

Figure 3: The three metric images acquired by Kostka in 1970.

3. PHOTOGRAMMETRIC PROCESSING

The photogrammetric reconstruction process consists of:

- phototriangulation (calibration, orientation and bundle adjustment),
- image coordinate measurement (automatic matching or manual procedure) and point cloud generation,
- modeling, i.e. surface generation and texture mapping for photo-realistic visualization.

3.1 Phototriangulation

A contour plot of the big statue, done by Prof. Kostka [Kostka, 1974], is also available (20 cm isolines, scale 1:100). From this plot some control points could be measured and used for the phototriangulation. Then, using the information in [Kostka, 1974] and the control points, we achieved the first approximations of the exterior and interior orientation parameters. The final orientation of the images is achieved using a bundle adjustment [Gruen et al., 2002] (Figure 4).

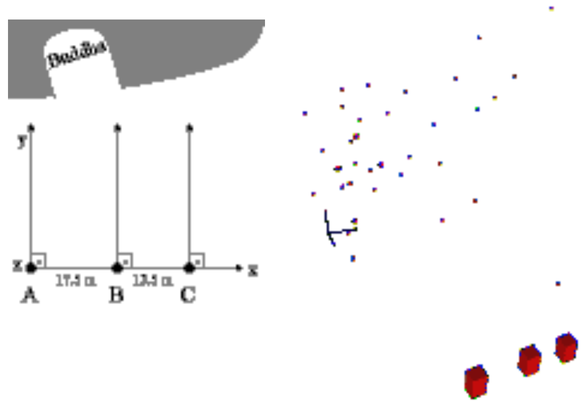

Figure 4: The acquisition procedure (left) and the recovered camera positions after the bundle adjustment (right).

3.2 Image coordinate measurement and point cloud generation

Image measurements are performed with automated and manual procedures. We first applied a commercial package (VirtuoZo) and then our self-developed matching software for the automated reconstruction of the statue. But, at the end, we used manual measurements to get a very precise, reliable and detailed 3D model of the Buddha.

3.2.1 Automatic measurements with commercial software

The 3D model of the Buddha statue was generated with the VirtuoZo digital photogrammetric system. The matching method used by VirtuoZo is a global image matching technique based on a relaxation algorithm [VirtuoZo NT, 1999]. It uses both grid point matching and feature point matching. The important aspect of this matching algorithm is its smoothness constraint satisfaction procedure. With the smoothness constraint, poor texture areas can be bridged, assuming that the model surface varies smoothly over the image area. Through the VirtuoZo pre-processing module, the user can manually or semi-automatically measure some features like ridges, edges and regions in difficult or hidden areas. These features are used as breaklines and planar surfaces can be interpolated, e.g. between two parallel edges. In VirtuoZo, first the feature point based matching method is used to compute a relative orientation between couples of images. Then the measured features are used to weight the smoothness constraints while the found approximations are used in the following global matching method [Zhang et al., 1992]. In our application, a regular image grid with 9 pixels spacing was matched using a patch size of 9×9 pixels and 4 pyramid levels. As result, a point cloud of ca 178 000 points is obtained (Figure 5). Due to the smoothness constraints and grid-point based matching very small features, like the folds of the dress were filtered or skipped.

Figure 5: 3D point cloud generated with VirtuoZo automatic matching on the metric images (ca 178 000 points).

3.2.2 Automated measurements with our software

A multi-photo geometrically constrained (MPGC) least squares matching software package, developed at our Institute, was applied to the metric images [Gruen et al., 2001, 2003]. The automatic point measurement works according to the following procedure:

1. Selection of one image as the master image. In our application, the center image was selected;
2. Extraction of a very dense pattern of feature points in the master image using the Foerstner operator;
3. Cross-correlation for each feature point to get the approximate matches for the following matching procedure (using also the epipolar geometry determined by phototriangulation);
4. MPGC matching for fine measurement, including patch reshaping parameters. MPGC exploits a priori known geometric information on orientation to constrain the solution and allows for the simultaneous use more than two images [Gruen, Baltsavias, 1988; Baltsavias, 1991].

In our application, for each feature point in the master image, all 3 metric images were employed for matching. With the MPGC approach, we can get sub-pixel accuracy matching results and 3D object coordinates simultaneously (Figure 6, left) and also, through covariance matrix computations, a good basis for quality control.

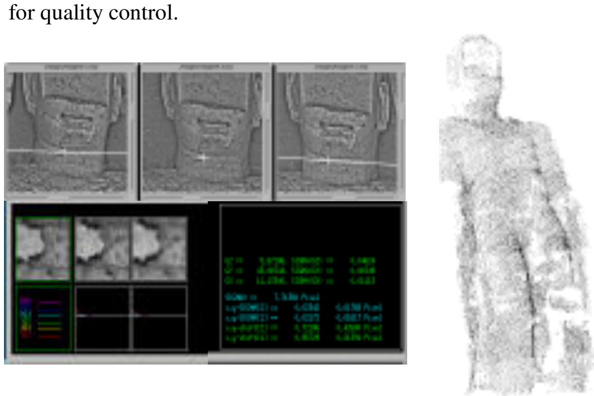

Figure 6: The GUI of our MPGC matching software, with the matching results and the computed 3D object coordinates (left). The measured point cloud (right).

The procedure resulted in fairly reliable and precise matching results. 49 333 points (without the surrounding rocks) and 73 640 points (with part of the surrounding rocks) were obtained. The point cloud data is shown in Figure 6, right. Although we use an automatic blunder and occlusion detection, some blunders are present in the final 3D point cloud. Moreover, there are some gaps in the cloud, mainly due to the shading effects caused by the variation of the illumination conditions during the image acquisition. Furthermore, many folds of the dress could not be reconstructed automatically, therefore these important small features had to be measured manually.

3.2.3 Manual Measurements

The dress of the Buddha is rich in folds, which are between 5 and 15 cm in width (Figure 7). The automated procedures could not recover these small details, therefore only precise manual measurements can reconstruct the exact shape and curvature of the dress.

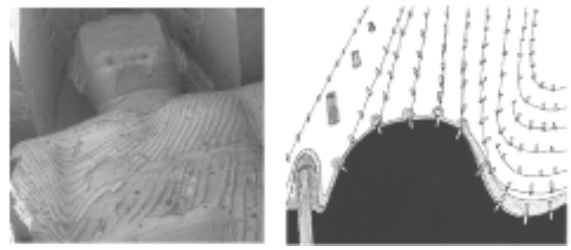

Figure 7: A closer view on the folds of the dress of the Buddha (left) and how they were constructed (right).

We imported the metric images in the VirtuoZo stereo digitize module [Virtuozo NT, 1999] and performed manual stereoscopic measurements. Three stereo-models are set up and points are measured along horizontal profiles of 20 cm increment while the folds and the main edges are measured as breaklines. With the manual measurement a point cloud of ca 76 000 points is obtained and the folds on the dress are now well visible (Figure 8).

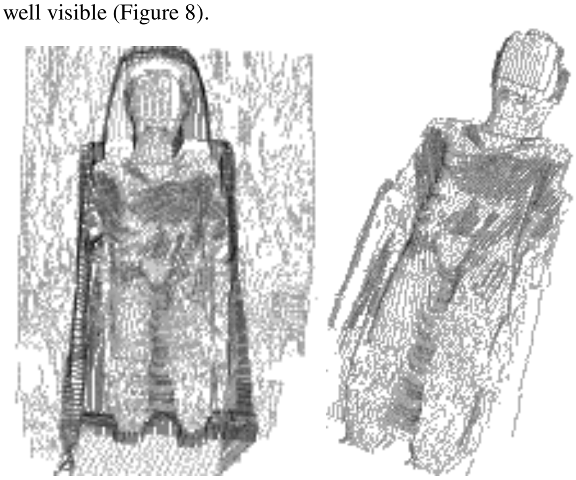

Figure 8: The point cloud of the manual measurement. The main edges and the structures of the folds, measured as breaklines, are well visible.

3.3 The modeling process

3.3.1 Automatic measurements

Due to the smoothness constraints and grid-point based matching, in both automated procedures the small folds on the body of the Buddha are not correctly reconstructed and the point cloud of the statue or the surrounding rock looks very smooth.

For the modeling, a 2.5D Delauney triangulation is performed and the final shaded model of the triangulated mesh is shown in Figure 9 and 10. The shaded models look a bit “bumpy“. This is due to small measurement errors and inconsistences in surface modeling.

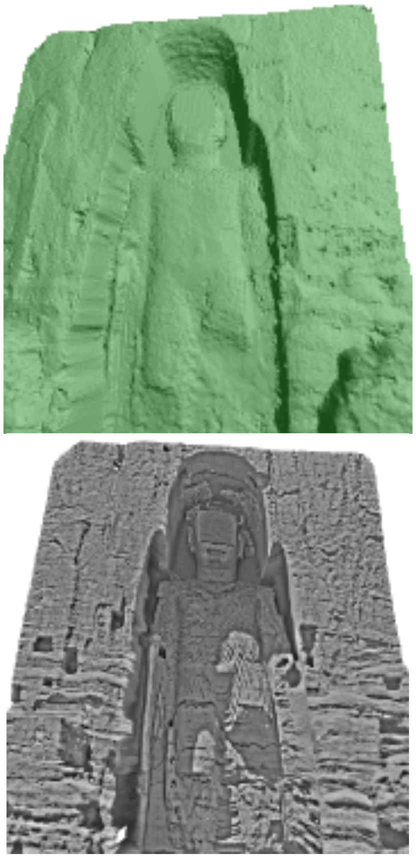

Figure 9: The triangulated shaded model (upper image) and the textured model automatically reconstructed with the commercial software.

Then the central image of the metric data set is mapped onto the 3D geometric surface to achieve a photo-realistic virtual model (Figure 9 and 10).

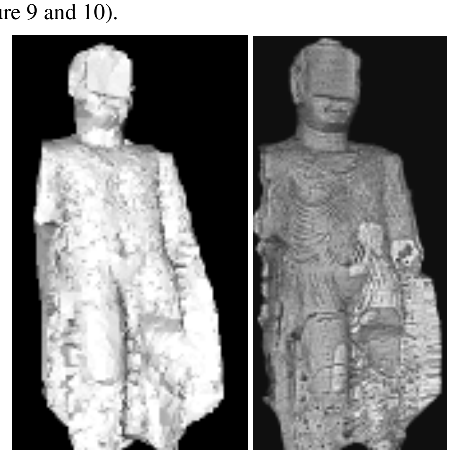

Figure 10: Visualization of the shaded and textured model generated with our matching software on the metric images.

3.3.2 Manual measurements

In the visualization of the point cloud of Figure 8 it is already possible to distinguish the shapes of the folds on the dress.

Figure 11: Visualization in wireframe mode of the 3D structures on the central part of the dress of the Buddha reconstructed after the triangulation of the manual measurements

This point cloud is not dense enough in some parts (except in the area of the folds) to generate a complete mesh with a commercial reverse engineering software. Therefore the generation of the surface is performed again with the 2.5D Delauney method, by dividing the measured point cloud in different parts. A mesh for each single point cloud is created and then all the surfaces are merged together with Geomagic Studio [www.geomagic.com]. The folds of the dress are now well reconstructed and modeled, as shown in Figure 11. The final 3D model, displayed in Figure 12, shows the completed reconstructed folds of the dress. Compared e.g. to Figure 9-upper, the new model represents a much better result. For photo-realistic visualization, the central image of the metric data set is then mapped onto the model, as shown in Figure 13.

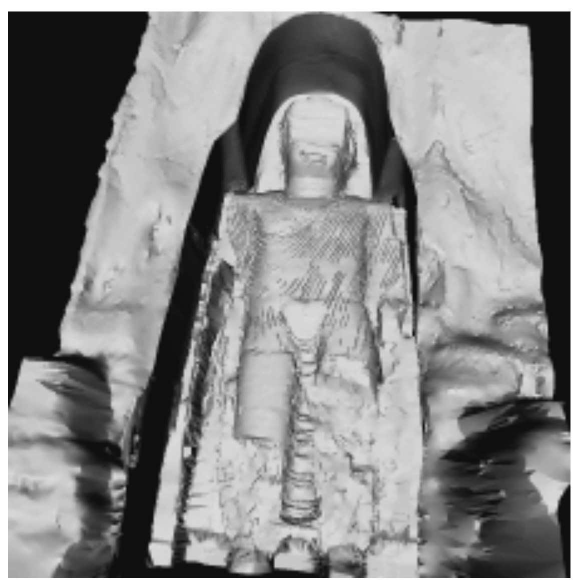

Figure 12: The shaded model of the Buddha, reconstructed with manual measurements on the three metric images.

4. 3D MODEL VISUALIZATION

Different tools are available to display 3D models, shareware and commercial software, with or without real-time performance, interactive or not. Often the visualization of a 3D model is the only product of interest for the external world and remains the only possible contact with the model: therefore visualization packages are very useful and must provide very realistic views.

The final 3D model generated with manual measurements is of rather big size and consists of ca 452 000 triangles.

One of the few portable formats to interactively display a 3D model like the reconstructed Buddha statue is the VRML. With free packages like Cosmo Player or Vrweb we can display and navigate through the model or automatically fly along some predefined paths (Figure 13). The final VRML model of the Great Buddha, including also part of the surrounding rock, occupies ca 98 Mb.

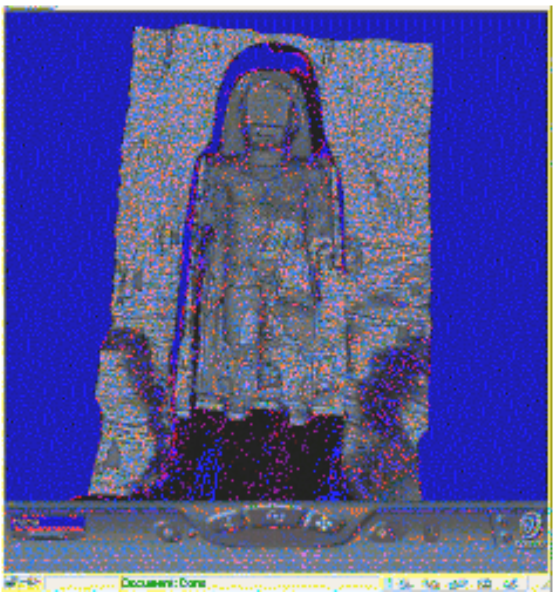

Figure 13: Visualization of the Buddha model with an Internet browser plug-in (Cosmo Player)

Computer animation software (e.g. Maya) is generally used to create animations of 3D models. An example is presented in http://www.photogrammetry.ethz.ch/research/bamiyan/anim/buddha.mpg.

Finally, a way to display attractive static views of 3D models is based on anaglyph images. An anaglyph mixes into one image a stereoscopic view using the complementarity of colours in the RGB channels. With coloured glasses, one can then filter the image and see the depth information of the model (Figure 15).

5. PHYSICAL RECONSTRUCTION

The 3D computer model that we generated with the manual procedure is used for a physical reconstruction of a scaled model of the Great Buddha. At the Institute of Machine Tools and Production, ETH Zurich, R.Zanini and J.Wirth have created a 1:200 model statue of the Great Buddha (Figure 14, right). The point cloud of the manual photogrammetric reconstruction is imported in a digitally programmed machine tool (Starrag NF100). The machine (Figure 14, left) works on polyurethane boxes and follows milling paths calculated directly from the point cloud. The physical model is created in three steps: (1) a roughing path, (2) a pre-smoothing path and (3) the final smoothing path. The time needed for preparing the production data was about 2 hours while the milling of the part itself was done in about 8 hours.

Figure 14: The milling machine used for the physical reconstruction of the Bamiyan Buddha (left) and an image of the 1:200 model (right).

6. CONCLUSIONS

The computer reconstruction of the Great Buddha of Bamiyan, Afghanistan has been performed successfully using digital photogrammetric techniques. We have presented here the results of the 3D model, based on automated point cloud generation and manual measurements on three metric images. But we produced also accurate results using simple Internet and tourist images where typical photogrammetric information (as interior and exterior orientation parameters) was not available. While automated matching methods provide for dense point clouds, they fail to model the very fine details of the statue, e.g. the folds of the robe. Therefore, only manual measurements allowed to generate a 3D model accurate and complete enough to serve as the basis for a possible physical reconstruction in Bamiyan.

We also reported how digital photogrammetry can be used to recover 3D models or technical documentation of historical monuments and sites. As next steps in our work we plan the following tasks:

- Measurement of the cave surface (backside of the Buddha after destruction);
- Generation of a photo-realistic 3D model of the cliffs and the extended vicinity;
- Modeling of the frescos inside the Great Buddha cave;
- Preparation of flyovers and animations.

Before the physical reconstruction of the Great Buddha in Bamiyan can be performed the damaged and endangered cliffs around the Buddha cave have to be stabilized. This is currently discussed at UNESCO and in other international circles.

A web site of the work has been established on our server and is available at
http://www.photogrammetry.ethz.ch/research/bamiyan/
with more technical details and animations.

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some Internet images of the Bamiyan statues and all the web sites where we found images and information on the Bamiyan statues.

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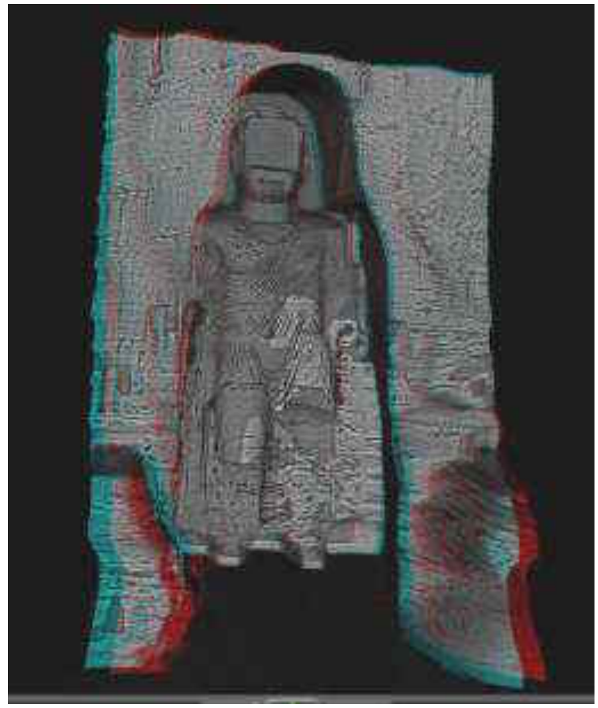

Figure 15: Anaglyph image of the reconstructed 3D model.