

# IMAGE- AND MODEL-BASED RECONSTRUCTION OF THE SMALL BUDDHA OF BAMIYAN, AFGHANISTAN

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### ABSTRACT:

This paper reports about our efforts to generate a 3D computer model of the Small Buddha of Bamiyan, Afghanistan. This was one of two famous standing Buddhas, both of them being destroyed by the Taleban in March 2001. This adds to our previous work on the reconstruction of the Great Buddha and the precise modelling of the larger landscape around it. The main problem here was the lack of one suitable dataset (e.g. old images) which could have been used alone for reconstruction. So we had to resort to different kind of data, in order to make good use of everything that was available: Two old amateur images, taken before the destruction, newly made images of the now empty niche (acquired for the 3D modelling of the niche) and a given contour map, produced from the metric images of a past photogrammetric campaign of the University of Kyoto. We describe the fairly complex procedures that enabled us to get, despite the insufficient material, quite acceptable results. This shows again how advanced photogrammetric techniques can be applied to reconstruct lost objects.

## 1. INTRODUCTION

The valley of Bamiyan, Afghanistan, situated in the middle of the Silk Road, was one of the major Buddhist centers from the second century up to the time when Islam entered the area in the ninth century. Two big standing Buddhas were carved out of the rock, probably during the fourth and fifth centuries AD. The larger statue was 53 meters high while the smaller Buddha measured 38 m. The two colossal statues were demolished in March 2001 by the Taleban, using mortars, dynamite, anti-aircraft weapons and rockets. At that time we were looking for a suitable dataset to demonstrate our procedures of reconstructing lost objects from old images. We picked the Bamiyan case because it was both technically challenging and practically relevant.

In former publications we described the successful 3D computer reconstruction of the Great Buddha, together with the now demolished frescos, the now empty niches, the complete rock face and a large terrain area around it, using different kinds of images, at different resolutions and quality (Gruen et al., 2003, 2004, 2006, Remondino and Niederoest, 2004). The results that we present here has to be seen as an extension of our previous work to reconstruct the archaeological site of Bamiyan. This paper describes the reconstruction of the Small Buddha statue and its integration into the current empty niche model.

Two image datasets and an existing contour drawing were used. First, a series of nine terrestrial images, acquired in August 2003, using a digital Sony Cybershot camera with 6 Megapixel image format was used to cover the empty niche after the destruction of the statue. The second dataset consists of two pictures, acquired using a 5.5 x 5.5 cm<sup>2</sup> analogue YASHICA frame camera with a focal length of around 80 mm in 1975 by a tourist, covering the statue before demolition. This dataset is characterised by very oblique viewing directions and a small base-distance ratio. In addition, the camera parameters, except a rough approximation of the focal length, were unknown.

The orientation of the niche dataset, including estimation of the camera parameters was done in a previous work. Ground control points, acquired during the field campaign, using a total station, were used to define the scale and the common coordinate system for consistent representations of all datasets in the final model. In addition, a surface model of the empty niche was generated in the past.

The orientation of the second dataset was done using different software systems. Special attention was paid to the calculation of the camera parameters. To define the scale of the model, control points, derived from the niche dataset, were introduced into the orientation procedure.

Afterwards an automatic surface model generation was conducted using our own software SAT-PP (SATellite image Precision Processing). Because of the weak acquisition geometry, only the breast and leg parts of the statue could be reconstructed reliably. The more complex structures, especially the regions around the arms and the folds of the clothing, required manual measurements and editing. Shoulders, face and feet are not well enough visible in the images. To fill these regions, an existing contour map, originally produced by an earlier Japanese photogrammetric mission to Bamiyan, was used. After a rough georeferencing, the contour lines of the problematic regions as well as the breast and the upper leg part were digitized. A first estimation of the equidistance was conducted using the generated body model. Therefore, a second surface model of the digitized regions could be generated.

The two surface models, one from the image measurements and one generated using contour lines, were co-registered using Geomagic Studio. Since the two datasets were available in the same coordinate system, a selective fusion could be conducted to generate a consistent depth model of the statue.

Subsequently a consistent model combining the statue and the niche data was generated by co-registration using corresponding points on the walls of the niche.

For texture mapping the statue dataset mentioned above was used. Because of lack of texture information in the invisible regions, only a not fully photorealistically textured model can be presented. In fact the missing texture was filled up by artificial texture patterns.

## 2. DATASETS

To reconstruct the Small Buddha a number of potential data sources, especially in form of images, were available from the web, in print media or from individual persons. But also a contour map was available. Most of the images were useless for the image-based reconstruction, because of the bad image quality or the low resolution. From all these potential data sources only three were used to reconstruct the Small Buddha.

- A. The first dataset is a series of nine terrestrial images, acquired in August 2003, using a digital Sony Cybershot camera, with 6 Megapixel image format. These images have been used to cover the empty niche after the demolition of the statue.
- B. The second dataset consisted of two amateur images, acquired using a 5.5 x 5.5 cm<sup>2</sup> analogue YASHICA camera with a focal length of approximately 80 mm, used 1975 by Hans Werner Mohm, covering large parts of the statue before demolition, see Figure 1. This dataset is characterised by very oblique viewing directions and a small base-distance ratio. In addition, the camera parameters, except a rough approximation of the focal length, were unknown. The advantage of these images is the fairly large image scale and therefore an adequate small object pixel size.



Figure 1. Images of the dataset B

- C. The third dataset is a contour map, published in (Higuchi, 2001), and generated by using metric images of a photogrammetric campaign, which are not available to the public, see Figure 2. The quality and resolution of the printed map, especially in steep regions, is insufficient, due to merging lines. In some regions it is not possible to separate them from each other. Furthermore, the equidistance and the absolute heights were unknown.



Figure 2. Contour line map (courtesy Prof. Minoru Inaba)

## 3. DATA PROCESSING SEQUENCE

The workflow for the extraction of 3D information from the three datasets and the combination of these data to generate a full 3D model of the Small Buddha, is shown in Figure 3.

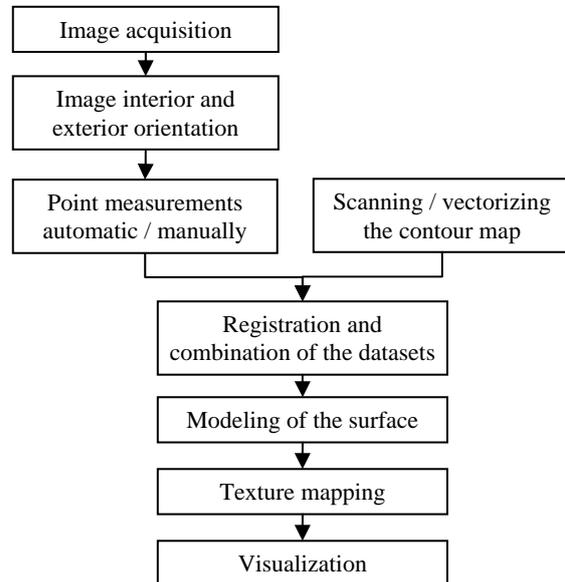


Figure 3. Workflow of the model reconstruction procedures

## 4. PROCESSING OF THE INDIVIDUAL DATASETS

### 4.1 Dataset A

The orientation of the niche dataset, including the estimation of the camera parameters was done in a previous work with a standard photogrammetric bundle adjustment using SGAP, an in-house developed software. Ground control points, acquired

during the field campaign, using a total station, were used to define the scale and the common coordinate system for a joint representation of all datasets in the final model. The standard deviation of the bundle adjustment was 1.9 micron, which is less than half a pixel in image space. The expected accuracy in object space was approximately three centimetres. Using this data, a 3D model of the empty niche could be generated.

The dataset A had to fulfil two mayor aims. It provided information for the camera calibration and the exterior orientation of the images of the dataset B and secondly, it enabled us to visualize the reconstructed statue in combination with the niche and its immediate surroundings.

#### 4.2 Dataset B

**4.2.1 Calibration and orientation:** The two analogue middle format images were scanned with a resolution of 10 micron, using the photogrammetric scanner Vexcel UltraScan 5000. The missing interior orientation parameters had to be determined by a simultaneous calibration, under consideration of the limited information provided by the two images. Therefore, the dataset B was combined with the dataset A by manual measurement of tie points. An automatic tie point measurement was conducted but the result was not usable, because of too large perspective differences between the two datasets. Figure 4 shows the distribution of the tie points between the two datasets.

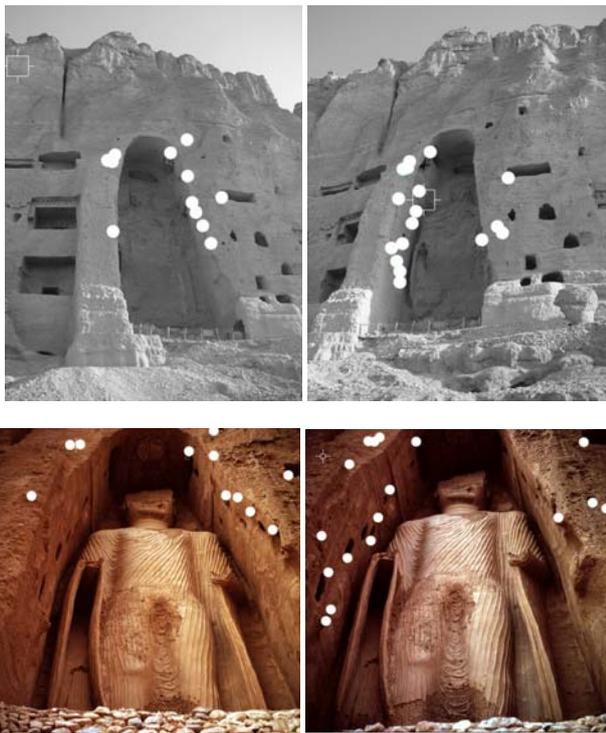


Figure 4. Tie point distribution between dataset A (upper row) and B (lower row)

In order to stabilize the system further, tie points between the images of the dataset B were measured using two different procedures. First, a manual measurement followed by the automatic tie point generation was performed, both conducted with the photogrammetric software LPS (Leica Photogrammetry Suite). The automatic tie point measurement

worked in an acceptable way. Nevertheless, under consideration of the poor network, using only two images, a second procedure was applied to increase the number of tie points. The SIFT operator (Lowe, 2004) was applied to find additional points. To improve the quality and number of measured points, the images were enhanced by using an adaptive histogram equalisation. Afterwards the SIFT operator was applied in a patch-wise mode to reduce processing time, memory consumption and the risk of mismatches. This procedure generated approximately 1700 points distributed over the whole image. Using the above mentioned software SGAP, a combined bundle adjustment of the datasets A and B was conducted. To preserve the high accuracy of the first dataset, the interior as well as the exterior orientation parameters of the dataset A were kept fixed. Consequently, the dataset B was fit into A using a constrained bundle adjustment. After an iterative procedure to eliminate mismatches of the SIFT procedure, a sigma0 of 0.9 pixel was obtained for the whole system. The accuracy of the exterior and interior orientation parameters, as well as the accuracy of the determined lens distortion parameters (Brown model) was sufficient to go ahead with the next processing steps. The lens distortion, as well as the shift of the principle point were removed from the images to avoid a wrong interpretation of the distortion parameters in the subsequently used software packages.

**4.2.2 Automatic Measurements:** The automatic Surface Model (DSM) generation was conducted using the software SAT-PP (SATellite image Precision Processing) (Zhang, 2005, Remondino et al., 2008). The results are shown in Figure 5. Because of the limited image quality, the small number of images (two), the oblique viewing directions and the small base-distance ration, the measurements were not usable to model the statue with sufficient accuracy and resolution. Nevertheless, some parts of the data, especially the breast and leg region, could be used for some following processing steps, e.g. the registration and determination of the equidistance of the contour line map.

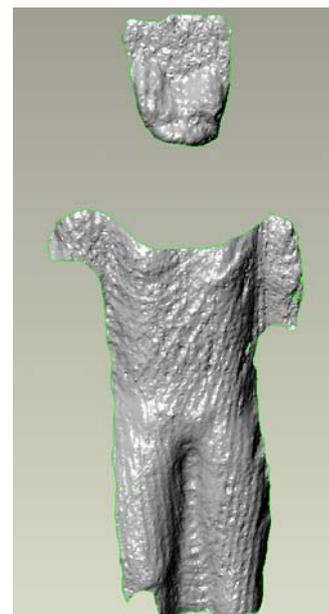


Figure 5. Result of the automatic image matching

**4.2.2 Manual measurements:** The manual measurements were conducted with the above mentioned software LPS. The aim was to preserve especially the folds of the dress and other small, but important items. Because of the local topography the images were acquired with very oblique viewing direction and a small base-distance ratio. This led to occluded areas in the upper parts of the shoulders, as well as at the upper parts of the arms, see Figure 6. The lower legs and feet were not visible at all. Therefore, the image-derived 3D data was not sufficient to model the whole statue without any other information.



Figure 6. Manual measurements with marked occlusions

### 4.3 Dataset C – contour map

To solve the problem of occluded parts, the third dataset - a contour map published in (Higuchi, 2001) had to be used. Describing a truly 3D object by a 2.5D contour map will cause some problems. In steep regions, the contour lines merge, which makes it difficult to interpret them correctly. In addition, information about the equidistance was missing. The latter problem could be solved using manual measurements. The difference in height between two areas, visible in both datasets, was measured from images and compared to the number of contour lines. Thus the equidistance was estimated with 10 cm. Using this information the contour lines were digitised by scanning and applying an automated line following routine from ArcMap. The absolute depth values were introduced using a starting point with an approximate depth, defined using the manual measurements. The derived point cloud covers the area from the middle of the breast down to the knees, which is jointly covered by the image-derived data. Additionally, the occluded shoulders, the head and some other small parts of the statue are covered.

## 5. COMBINATION OF THE DATASETS

The co-registration of the datasets A and B was already done during the joint bundle adjustment. Both datasets are present in the same coordinate system.

The co-registration of the dataset B and C was conducted in the following manner. The contour lines as well as the manual measurements were converted into dense 3D vectors with a point interval of one centimetre, to preserve the high frequency information. These two structured point clouds were co-registered using the software Geomagic Studio in a two step procedure. First, initial transformation parameters were calculated by manual measurements of common points. In a second step the two surfaces were accurately co-registered by the ICP procedure of Geomagic Studio, see Figure 7. After co-registration the mean distance between the two datasets was 9.9 cm.

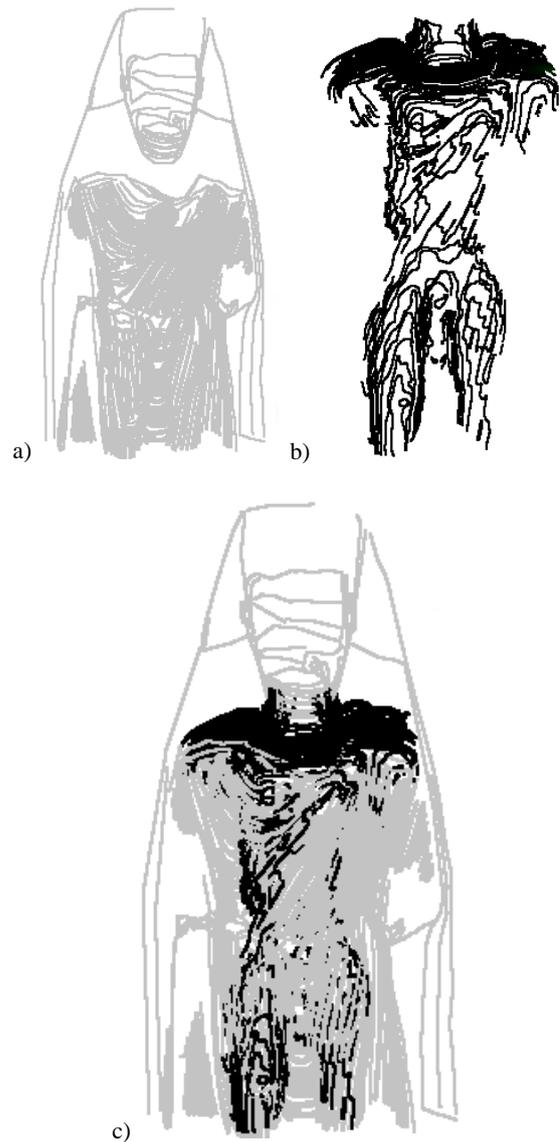


Figure 7. Co-registration of surfaces using Geomagic Studio  
 a) Manual image measurements  
 b) Digitized contour lines  
 c) Co-registered datasets

The difference of around 10 cm in the registration result was mainly due to the folds, which were included in the manual measurements, but not in the contour data. Concerning the fact, that the depth of these structures is between 10 cm to 20 cm above the average surface depth and the manually measured

point cloud consists of approximately 30 percent of these points, the result (mean distance) without these points would be reduced to less than 6 cm, which is an acceptable result.

In regions with overlapping datasets, the data had to be fused or the overlaps had to be removed to avoid inconsistencies during the meshing procedure. Here, the regions were combined by removing the less accurate dataset in a particular region. Therefore, the manual measurements were used as reference data, the contour information was used to fill the occluded parts, e.g. the upper parts of the shoulders.

### 5.1 Modelling of the surface

To generate a surface of the full object, the software Geomagic Studio was used. First the automatic meshing function was activated. This procedure was not successful, because the implementation of the software could not handle the line-wise structure of the dataset, with a high point density in line direction and less density across the line. Some tests were done to eliminate this inconvenience under preservation of the high frequency information of the dataset. Nevertheless, the result contained a number of holes and errors which had to be filled and removed. The result is a consistent surface of the object, see Figure 8.



Figure 8. Result of the 3D modelling of the full dataset using Geomagic Studio

## 6. VISUALIZATION

The texture mapping was done using one image of the dataset B with an in-house developed software. To visualize the extracted data with around 600k triangles and to achieve a satisfying result the open source software system Blender was used (Blender, 2008). It is an open source 3D content creation suite, available for all major operating systems under the GNU General Public License. Among other features it can be used for modelling, texture mapping, animation and rendering, comparable with a commercial system, e.g. Maya (Autodesk). The model data can be directly imported into the software. Using this information the object can be visualized inside the software in real-time and virtual reality models can be exported in different formats (VRML, COLLADA, etc.). To generate movies and high resolution images of the model different additional steps are necessary. For example, different illumination sources and camera positions, as well as the camera path for the camera movement have to be defined in an iterative procedure. These steps require, depending on the experiences of the operator, some time to become familiar with.

Because of the lack of texture information in the occluded regions, a not fully photorealistically textured model is presented in Figure 9. In fact the missing texture was filled up by artificial texture patterns.



Figure 9. Textured model of the Small Buddha

## 7. CONCLUSIONS

We have described the procedures that led to the 3D modelling of the Small Buddha of Bamiyan, Afghanistan. We have used two old amateur images of the destroyed Buddha figure itself, some Sony Cybershot images for the modelling of the now empty niche and a contour plot, generated from metric images of a past photogrammetric campaign. The local topography allowed only images to be taken with very skew angles. Therefore many parts of the Buddha figure remained occluded in the images and had to be reconstructed from the contour plot. Given the difficult data configuration and low quality of the primary data, automated methods of model generation do not

deliver the required results in terms of completeness of the object and reliability of the measurements. Under these conditions high quality results need still manual measurements. We believe that the results of the reconstruction (estimated accuracy of the surface elements: around 5 cm on a 38 m high statue) are quite acceptable.

Our work on the Small Buddha is not finished yet. We still see some room for improvement, in particular by manually digitizing the contours (so far we applied an automatic line following algorithm) in the problematic regions, and by using other old images which give information on the now hidden and thus missing parts (lower legs, feet and other small model sections).

As described, this image- and model-based reconstruction resulted in a sequence of quite complicated procedures. But the result of this work, a digital, textured 3D model justifies the efforts. It shows the capabilities of advanced digital photogrammetric techniques, whose products can not only be used for digital representations, but also for physical reconstructions of the situation before the demolition of the objects of interest.

This work should be considered as a contribution to documentation, restoration and protection of cultural heritage objects, and therefore serves to maintain the knowledge about culture and history for the coming generations.

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