RECONSTRUCTION OF THE GREAT BUDDHA OF BAMIYAN, AFGHANISTAN

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ABSTRACT:

In the valley of Bamiyan, Afghanistan, ca 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. Our group did the computer reconstruction of the statue, which will serve as a basis for the physical reconstruction. The work is done in parallel with three different data sets of images and in this paper we report the first results of the 3-D reconstruction of the Great Buddha.

1. INTRODUCTION

In the great valley of Bamiyan, 200 km north-east of Kabul, Afghanistan, two big standing Buddha statues were carved out of the sedimentary rock of the region, at 2500 meters of altitude. The Emperor Kanishka ordered their construction 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. The town of Bamiyan, situated in the middle of the Silk Route, was one of the major Buddhist centres from the second century up to the time that Islam entered the valley in the ninth century. The larger statue was 53 metres high while the smaller Buddha measured 35 m. They were cut from the sandstone cliffs and they were covered with mud and straw mixture to model the expression of the face, the hands and the folds of the robe. To simulate these folds of the dress, cords were draped down onto the body and were attached with wooden pegs. 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 colours and they were decorated with dazzling ornaments. They are considered the first series of colossal cult images in Buddhist art.

The two statues were demolished on March 2001 by the Taleban, using mortars, dynamite, anti-aircraft weapons and rockets. The Buddhists, the world community, ONU and UNESCO failed to convince the Taleban to leave such works of cultural heritage.

After the destruction, a consortium was established with the goal to rebuild the Great Buddha of Bamiyan at original shape, size and place. This initiative is lead by the global heritage Internet society *New7Wonders*, 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 will serve as a basis for the physical reconstruction. Using our model, first a statue at 1/10 of the original size will be built and displayed in the Afghanistan Museum in Switzerland. This will be used to study materials and construction techniques to be applied in the final rebuilding at full size.

In this paper we present the first results of the reconstruction of the 3-D model of the Great Buddha of Bamiyan.

The work is done using three different types of imagery in parallel:
1. a set of images acquired on the Internet (amateur images);
2. three metric images acquired in Bamiyan in 1970 by Prof. Kostka, Technical University of Graz [Kostka, 1974];
3. a set of touristic images acquired by Harald Baumgartner who visited the valley of Bamiyan between 1965 and 1969.

We are still processing the third data set, while results from the first two are already available. The reconstruction is performed with automatic and manual procedures. Only the computer model generated with the manual measurements on the metric images will be used for the physical reconstruction of the Great Buddha, but in this paper we report all the results of the first two data sets.

Figure 1: The Great Buddha of Bamiyan before the destruction (left); the explosion of March 2001 (center) and the rests after the destruction (right).

2. METHODOLOGY OF PROCESSING

The reconstruction process consists of phototriangulation (calibration, orientation and bundle adjustment), image coordinate measurement (automatic matching or manual procedure), point cloud and surface generation, texture mapping and visualization.

Out of the 15 images found on the Internet, four of these were selected for the processing (Figure 2 - A, B, C, D): two in front of the big Buddha, one from the left side and one from the right side of the statue. All others were not suitable for photogrammetric processing because of very low image quality, occlusions or small image scale.
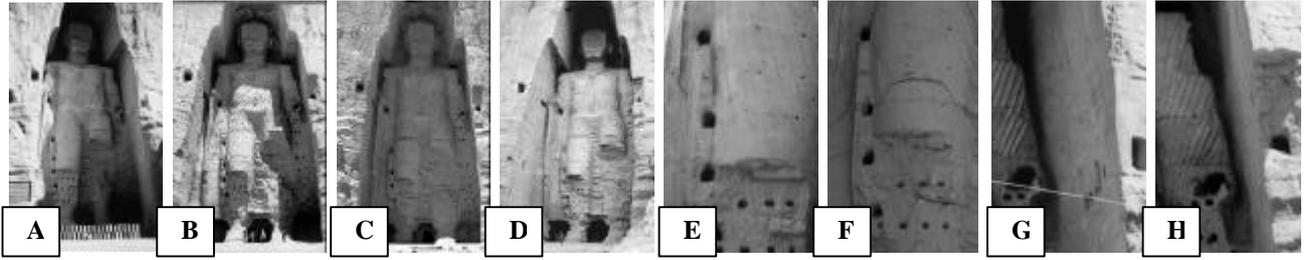
Figure 2: The Internet data set (A, B, C and D) used for the 3-D reconstruction.
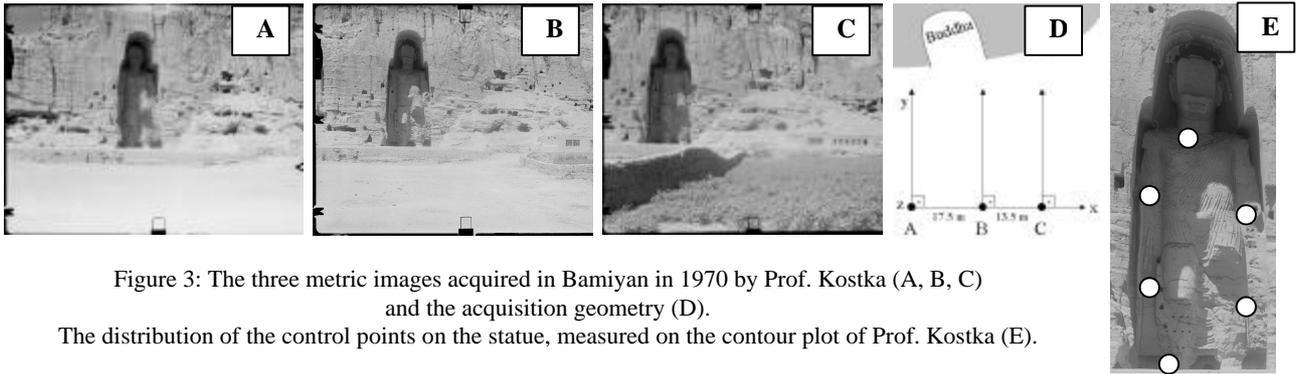Changed details between the images (E/F and G/H).

Figure 3: The three metric images acquired in Bamiyan in 1970 by Prof. Kostka (A, B, C)
and the acquisition geometry (D).
The distribution of the control points on the statue, measured on the contour plot of Prof. Kostka (E).

The main problems of these images are their differences in size and scale, the unknown pixel size and camera constant and most of all the different times of acquisition; therefore some parts visible in one image are missing in others (Figure 2 - E, F, G, H). Also the illumination conditions are very different and this can create problems with automatic matching procedure.

The metric images were acquired in August 1970 with a TAF camera [Finsterwalder and Hofmann, 1968]. The TAF (Terrestrische Ausrüstung Finsterwalder) is a photo-theodolit camera (Figure 4) that acquires photos on 13x18 cm glass plates. Two fiducials marks are present on the longer sides of the photos while a moving pointer signs the horizon with an index that moves vertically. The original photos were scanned by Vexcel Imaging Inc with the ULTRA SCAN 5000 at a resolution of 10 micron. The resulting digitized images resulted in 16930 x 12700 pixels each (Figure 3 - A, B, C). 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 orientation process.

2.1 Interior orientation

2.1.1 Internet images

For every image, the pixel size and a focal length are assumed, as well as the principal point, fixed in the middle of the images. With this last assumption, we consider the size of the found images as the original dimension of the photo, while they could be just a part of an originally larger image. The assumed pixel sizes are between 0.03 mm and 0.05 mm.

2.1.2 Metric images

In all TAF images the principal point is defined as the intersection of the straight line joining the two fiducials marks on the upper and lower side of the image and the horizontal line passing through the horizontal index defined on the right side of the image (Figure 4). The focal length of the camera is 160.29 mm [Kostka, 1974].
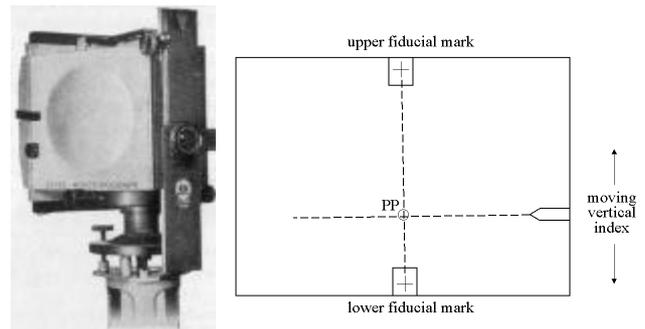

Figure 4: The TAF camera (left) and
the interior orientation of the images (right)

2.2 Exterior orientation

2.2.1 Internet images

As no other information is available, we first performed an interactive determination of the camera positions, varying also the value of the focal length and using some control points measured on the contour plot of Prof. Kostka. Then we refined these approximations with a single photo spatial resection solution.

2.2.2 Metric images

In [Kostka, 1974] the acquisition procedure is described (Figure 3-D). The images were acquired in normal case, with a double baseline and a distance of ca 130-150 m from the statue. Using this information and some control points measured on the contour plot we achieved the first approximations of the exterior orientation.

2.3 Bundle adjustments

The final orientation of both data sets was achieved using bundle adjustments and the control points measured on the

contour plot of Kostka. The image correspondences for triangulation were obtained semi-automatically with adaptive least squares matching [Gruen, 1985]. The results of the bundles are summarized in Table 1, where σ_0 represents the standard deviation a posteriori of unit weight and $\bar{\sigma}_{x,y,z}$ are the average standard deviations of the object point coordinates located on the Buddha itself and on its immediate vicinity.

	No. tie points	σ_0 [mm]	$\bar{\sigma}_x$ [m]	$\bar{\sigma}_y$ [m]	$\bar{\sigma}_z$ [m]
Internet	31	0.016	0.082	0.177	0.330
Metric	35	0.019	0.076	0.078	0.141

Table1: Results of the bundle adjustment of the two data sets.

In the metric block, the control point distribution covered just a small part of the images (the statue) while in the Internet block, the control information were more distributed on the whole images. Figure 6 shows the configuration of the cameras of the Internet data set.
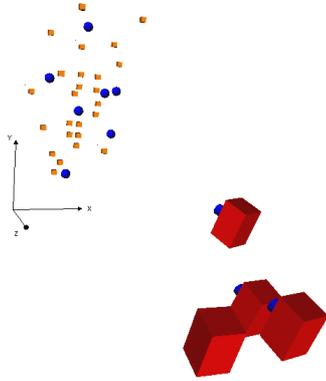

Figure 5: A view on the recovered camera poses of the Internet images with tie and control points

2.4 Surface reconstruction

After the establishment of the adjusted image blocks, the 3-D reconstruction of the statue was performed with automatic procedures on both data sets and with manual measurements only on the metric images. The results of the manual measurements will serve for the physical reconstruction of the statue. In all cases, Wallis filtering was applied to remove the low frequencies and enhance the texture information in the images.

2.4.1 Automatic reconstruction from the Internet images
A multi-image geometrically constrained least squares matching software package developed at our Institute was applied on the Internet images [Grün et al., 2001]. The automatic surface reconstruction works in fully automated mode according to the following procedure:
1. Selection of one image as the master image.
2. Extraction of a very dense pattern of feature points in the master image using the Moravec operator. At this stage, the master image is subdivided into 7×7 pixel image patches and within each patch only one feature point which gains the highest interest value is selected.
3. For each feature point, using the epipolar geometry determined in photo-triangulation, we get the approximate matches for the following MPGC (Multi-Photo

Geometrically Constrained) matching procedure by standard cross-correlation technique.
4. MPGC is applied for fine matching, including patch reshaping. MPGC exploits a priori known geometric information to constrain the solution and simultaneous use of more than two images (Gruen, 1985; Gruen et al., 1988; Baltsavias, 1991).

The difficulties of this data set lie in the large differences between the images, due to the different acquisition time, the illumination conditions and the different image scales.

2.4.2 Automatic reconstruction from the metric images
The 3-D model of the Buddha statue was generated with VirtuoZo digital photogrammetric systems. The matching method used by VirtuoZo is a global image matching technique based on 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 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, images B and C of the metric data set were used to reconstruct the 3-D model. A regular image grid with 9 pixels spacing was matched using a patch size of 9×9 pixels and 4 pyramid levels. As result, 356×311 3-D points were generated. Due to the smoothness constraint and grid-point based matching, the very small features of the dress were filtered or skipped. Therefore these important small features had to be measured manually.

2.4.3 Manual reconstruction from the metric images
The dress of the Buddha is rich of folds, which are between 5 and 10 cm in width (Figure 6).

Figure 6: The folds on the dress of the Great Buddha that are reconstructed with manual measurements

Only precise manual measurements can reconstruct the exact shape and curvature of the dress. Therefore the metric images are imported to the VirtuoZo stereo digitize module (Virtuozo NT, 1999) and manual stereoscopic measurements are performed. The three stereo-models A/C, A/B and B/C (Figure 3) 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.

3. RESULTS OF THE RECONSTRUCTION

3.1 Internet images

From the Internet data we used only three images for the MPGC matching algorithm. A point cloud of ca 6000 points is obtained. Some holes are present in the results (Figure 7, left) because of surface changes due to the different time of image acquisition and to the low texture in some areas. For the conversion of the point cloud to a triangular surface mesh, a 2.5D Delauney triangulation is applied. The texturized 3-D model is shown in Figure 7.
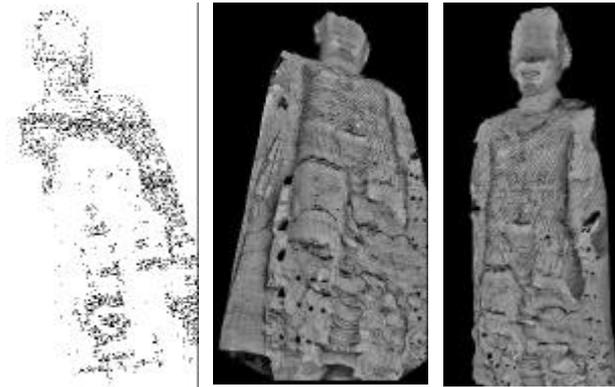
Figure 7: Point cloud obtained from the internet images (left). 3-D model of the Buddha displayed in texturized mode (central and right image)

3.2 Metric images - Automatic measurements

Using VirtuoZo we got an entire Buddha model including parts of the surrounding rocks. A very dense point cloud of 178000 points is obtained (Figure 8).
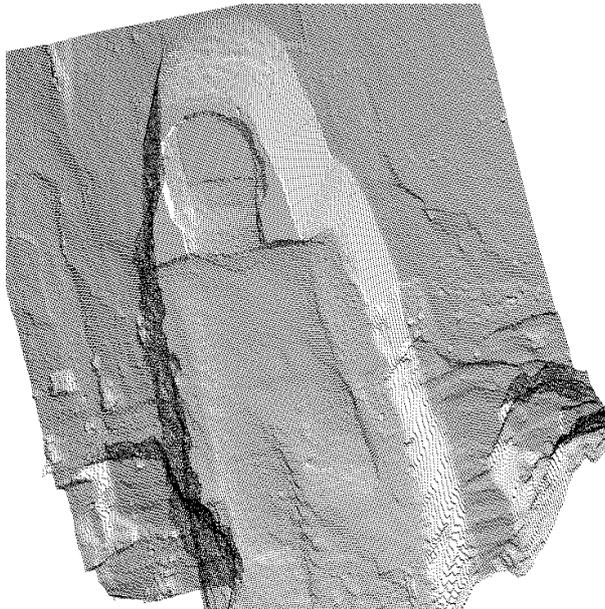

Figure 8: 3-D point cloud generated with automatic matching on the metric images

The statue as well as the rock around it are well reconstructed, but due to the smoothness constraint and grid-point based matching the small folds on the body of the Buddha are not visible.

For the modeling, a 2.5D Delaunay triangulation is performed: without losing its topology, the 3D surface model of the Buddha is expanded to a plane by transforming the cartesian coordinate system to a cylinder coordinate frame. In the defined rqz cylinder frame, z is the vertical cylinder axis crossing the model center and parallel to the original Y-axis of the cartesian object coordinate system. r is the euclidean distance from the surface point to the z-axis and q is the angle around the z-axis. The 2.5D triangulation was done in the qz plane and the final shaded model of the triangulated mesh is shown in Figure 9.
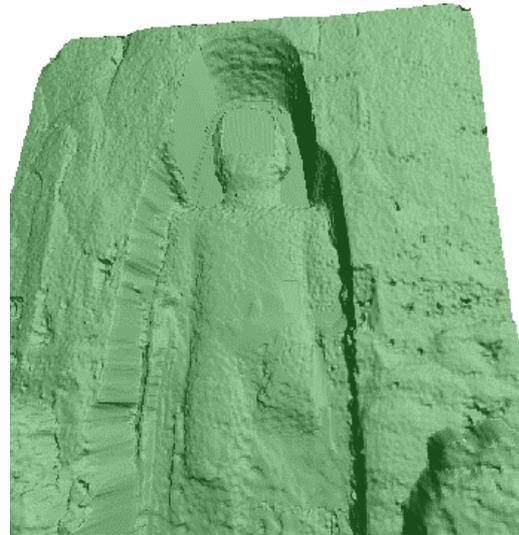

Figure 9: The triangulated shaded model

Then the central image of the metric data set is mapped onto the 3-D geometric surface to achieve a photorealistic virtual model (Figure 10). The lower part of the legs are not modeled because in the used stereomodel the legs were not visible.

Figure 10: Visualization of 3-D model of the Great Buddha in textured mode

3.3 Metric images - Manual measurements

With the manual measurement a point cloud of ca 28000 points is obtained. In the point visualization of Figure 11 it is already possible to distinguish the shapes of the folds on the dress.
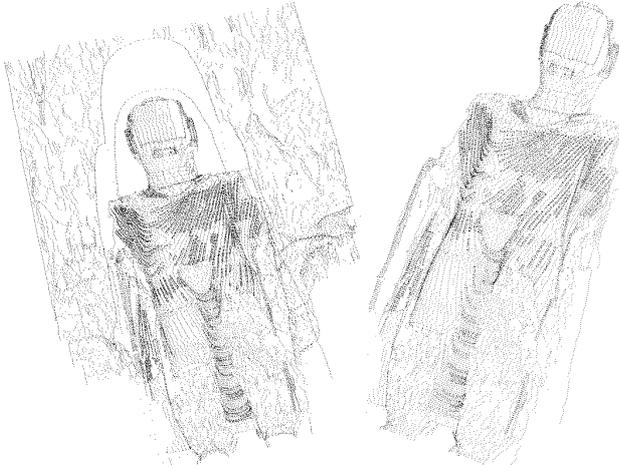

Figure 11: The point cloud of the manual measurement. The main edges and the structures of the folds, measured as breaklines, are well visible

The following surface triangulation is able to reconstruct the features of the dress (Figure 12). The final 3-D model is presented in Figure 13.
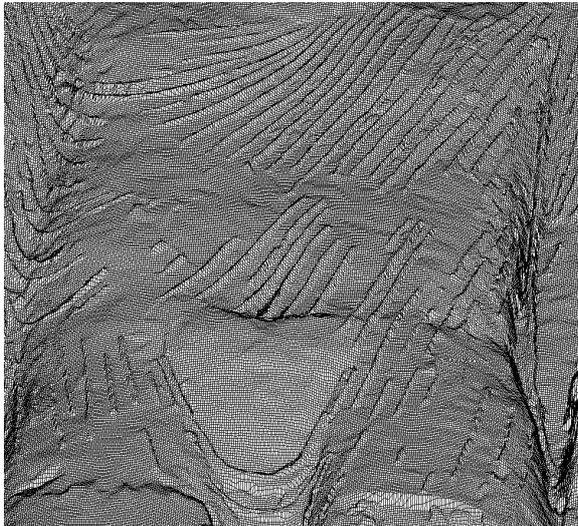

Figure 12: Visualization in wireframe mode of the 3-D structures on the central part of the dress of the Buddha

4. PHYSICAL RECONSTRUCTION

The 3-D computer model that we reconstructed with the manual procedure is used for the physical reconstruction of the Great Buddha. At the Institute of Machine Tools and Production, ETH Zurich, R.Zanini and J.Wirth have recreated a 1:200 model statue of the Great Buddha. The point cloud of the photogrammetric reconstruction is imported in a digitally programmed machine tool (Starrag NF100) without any further processing (Wirth, 2002). The machine 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.
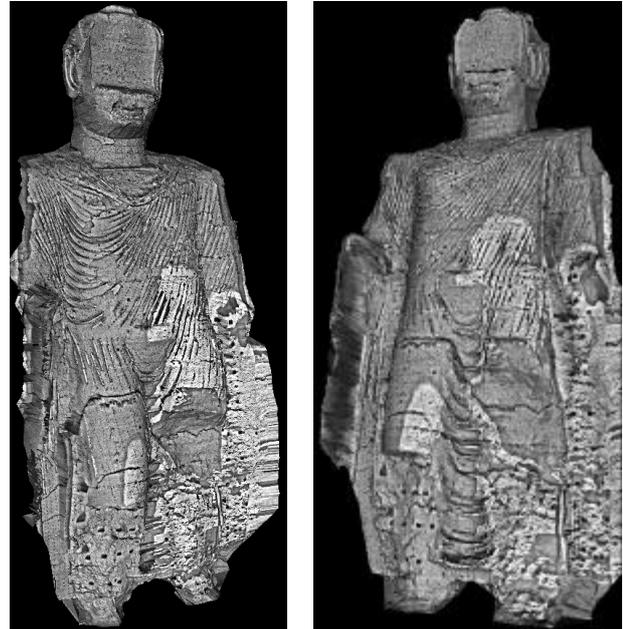

Figure 13: The texturized 3-D model of the statue created with manual measurements on the metric images

5. CONCLUSIONS

The computer reconstruction of the Great Buddha of Bamiyan, Afghanistan has been performed successfully using various digital photogrammetric techniques. We have presented here three versions of the 3D model, based on (a) automated point cloud generation using four internet images, (b) automated point cloud generation using three metric images, (c) manual measurements using three metric images. While the 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. Also, some important edges are missed. Only manual measurements allow to generate a 3-D model which is accurate and complete enough to serve as the basis for the physical reconstruction. Therefore, we will use the results of version (c) for the physical reconstruction of the statue. With a pixel size of 10 micron (1 cm on the object) manual measurements can be done with a relative accuracy of about 1-2 cm. While such high accuracy is necessary to model the folds (5 - 10 cm in size) correctly, it is surely more than sufficient to represent the overall form of the 53 m high statue in very close resemblance to the original. The problems encountered here with the orientation of amateur images and with automated matching could be solved in an acceptable manner. The main difficulties of this project consisted in the transition from the point cloud (including breaklines) to a surface model which can satisfy high modeling and visualization demands. Since automated image matching does not take into consideration the geometrical object surface conditions it is very difficult to turn such more or less randomly generated point clouds into TIN or wireframe structures of high quality and without losing essential information. Even when measurements are done in manual mode it is crucial for the operator to understand the functional

behaviour of the subsequently activated 3-D modeler. In this context an on-line modeler would be very beneficial. During point measurements the results of this modeler could be injected into the stereomodel at any time and the operator could control the agreement of the on-line model with the measurements and the structure of the object. In our case we had to intervene manually into the surface modeling process more than we had expected originally.

Currently the fundraising efforts are underway to support the physical reconstruction of the Great Buddha of Bamiyan.

A web site of the work has been established on our server and is available at

http://www.photogrammetry.ethz.ch/research/bamiyan/

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