

## MODELING AND VISUALIZATION OF THE GREAT BUDDHA STATUE IN BAMMIYAN, 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 can serve as basis for the physical reconstruction. In this paper we report the results of the 3D reconstruction of the Great Buddha, with particular attention to the modeling and visualization of the measurements.

**KEYWORDS:** Cultural Heritage, Orientation, Matching, 3D Reconstruction, Surface modeling, Visualization, Photo-realism

### 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 led by the global heritage Internet society New7Wonders [[www.new7wonders.com](http://www.new7wonders.com)], 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 can serve as basis for the physical reconstruction.

In this paper we present the results of the computer reconstruction of the Great Buddha of Bamiyan, with particular attention to the modeling and visualization of the 3D models. The computer reconstruction is done using three different types

of imagery in parallel and performed with automatic and manual procedures.

### 2. AVAILABLE IMAGES OF THE GREAT BUDDHA

Our work is based on the use of three different types of imagery in parallel:

1. A set of images (Figure 1 - A, B, C, D) acquired from the Internet ("Internet images");
2. A set of tourist-type images (Figure 1 - E, F, G) acquired by Harald Baumgartner, who visited the valley of Bamiyan between 1965 and 1969 ("Tourist images");
3. Three metric images (Figure 2) acquired in 1970 by Prof. Kostka, Technical University of Graz [Kostka, 1974].

We are still processing the second data set, while results of the other two sets are already available.

Originally our interest in the reconstruction of the statue was a purely scientific one. We planned to investigate how such an object could be reconstructed fully automatically using just amateur images taken from the Internet. Then, after learning about the efforts to actually rebuild the Great Buddha we decided to get involved in the project beyond a purely scientific approach and to contribute as much as we could with our technology to the success of the work.

Out of 15 images found on the Internet, four were selected for the processing (Figure 1). All others were not suitable for photogrammetric processing because of very low image quality, occlusions or small image scale. The images present differences in size and scale, they have 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. Also the illumination conditions are very different and this can create problems with automatic matching procedure

The metric images were acquired with a TAF camera [Finsterwalder et al., 1968], a photo-theodolite 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 2). Their acquisition procedure is known as well as the interior parameters of the camera. [Kostka, 1974]

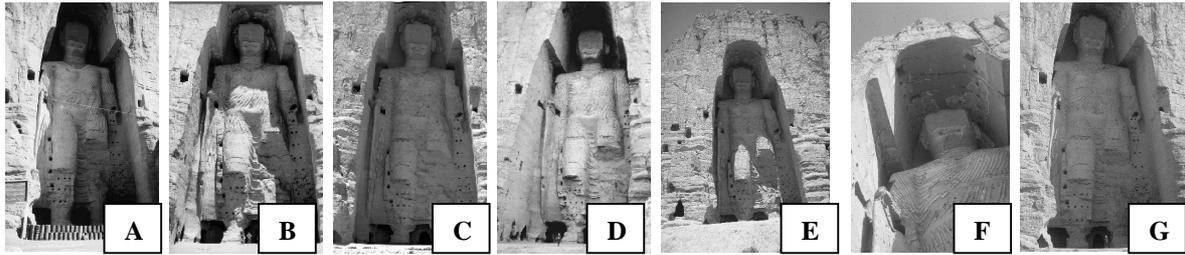


Figure 1: The Internet data set (A, B, C and D) used for the 3D reconstruction. Three images of the tourist data set (E, F and G) that we are still processing.



Figure 2: The three metric images acquired in Bamiyan in 1970 by Prof. Kostka (A, B, C)

### 3. PHOTOGRAMMETRIC 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.

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.

#### 3.1 The Internet Images

The main scientific challenge here lies in the facts that no typical photogrammetric information about these images is available and that existing automated image analysis techniques will most probably fail under the given circumstances. After the establishment of an adjusted image block (Figure 3) [Gruen et al., 2002], the 3D reconstruction of the statue was performed with a multi-image geometrically constrained least squares matching software package developed at our Institute [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. The master image is subdivided into  $7 \times 7$  pixel image patches and within each patch is selected the point that has the highest interest value.
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].

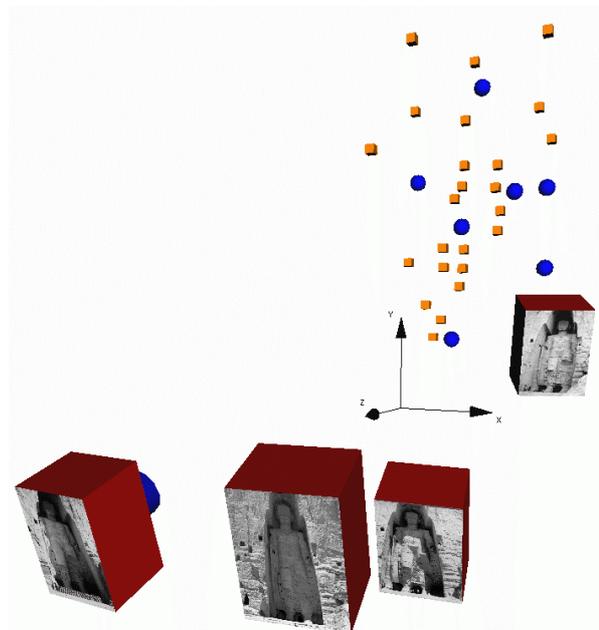


Figure 3: A view on the recovered camera poses of the Internet images with tie and control points

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.

A point cloud of ca 6000 points is obtained. Some holes are present in the results (Figure 6, left) because of surface changes due to the different time of image acquisition and to the low texture in some areas.

#### 3.2 The metric images

Using the information in [Kostka, 1974] and some control points measured on the contour plot, we achieved the first approximations of the exterior and interior parameters. The final orientation of the images is achieved using a bundle adjustment [Gruen et al., 2002]. Then automated and manual procedures are applied to reconstruct the 3D model of the statue.

### 3.2.1 Automatic Measurements

The 3D model of the Buddha statue was generated with Virtuozo digital photogrammetric systems. The matching method used by Virtuozo is a global image matching technique with 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 3D model. A regular image grid with 9 pixels spacing was matched using a patch size of  $9 \times 9$  pixels and 4 pyramid levels. As result, a point cloud of ca 178 000 points is obtained (Figure 4).

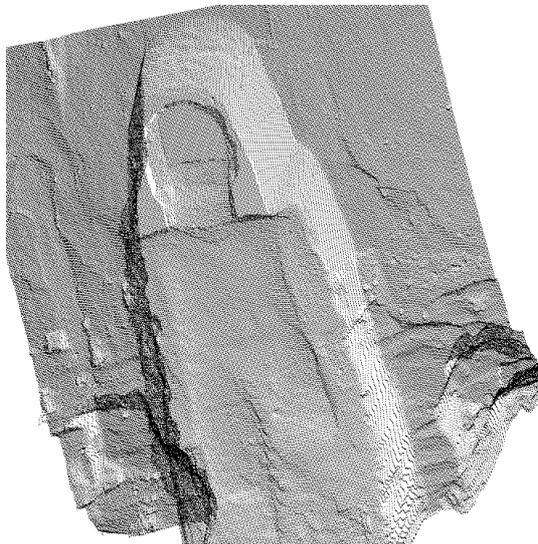


Figure 4: 3D point cloud generated with automatic matching on the metric images (ca 178 000 points)

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.

### 3.2.2 Manual Measurements

The dress of the Buddha is rich of folds, which are between 5 and 10 cm in width. Therefore 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 2) 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 (Figure 5) and the folds on the dress are now well visible.

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



Figure 5: The point cloud of the manual measurement. The main edges and the structures of the folds, measured as breaklines, are well visible

## 4. RESULTS OF THE MODELING

### 4.1 Internet images

For the conversion of the point cloud to a triangular surface mesh, a 2.5D Delauney triangulation is applied. Due to some holes in the cloud, the created mesh surface includes some big faces. Then the model is texturized with one image of the data set and the result is shown in Figure 6, right.

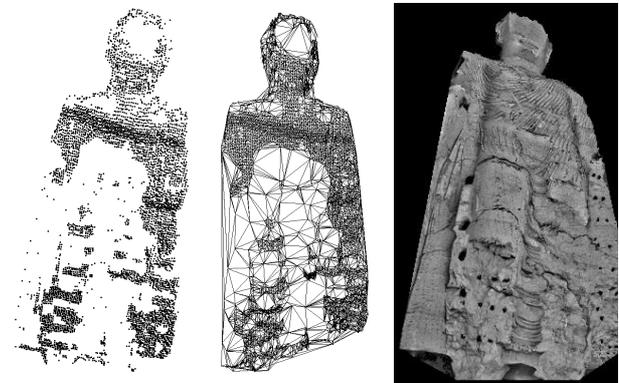


Figure 6: Point cloud obtained from the internet images (left). Mesh surface of the Buddha (central) and 3D model displayed in textured mode (right image)

### 4.2 Metric images - Automatic measurements

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

For the modeling, a 2.5D Delauney 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  $\rho\theta\zeta$  cylinder frame,  $\zeta$  is the vertical cylinder axis crossing the model center and parallel to the original Y-axis of the cartesian object coordinate system.  $\rho$  is the euclidean distance from the surface point to the z-axis and  $\theta$  is the angle around the z-axis.

The 2.5D triangulation was done in the  $\theta\zeta$  plane and the final shaded model of the triangulated mesh is shown in Figure 7. The model looks a bit “bumpy”. This is due to small measurement errors and inconsistencies in surface modeling.

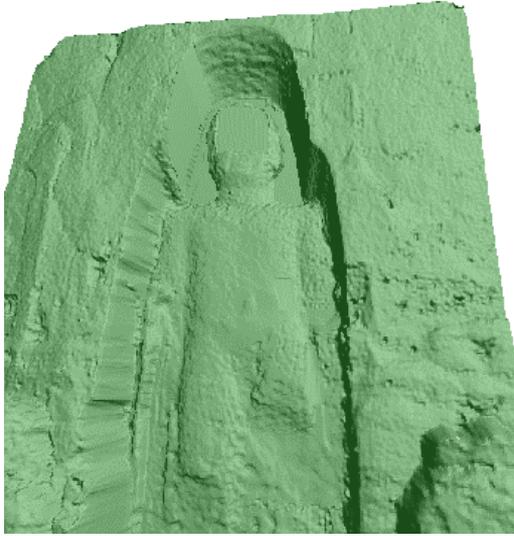


Figure 7: The triangulated shaded model automatically reconstructed

Then the central image of the metric data set is mapped onto the 3D geometric surface to achieve a photorealistic virtual model (Figure 8). The lower part of the legs are not modeled because in the used stereomodel the legs were not visible.



Figure 8: Visualization of textured 3D model generated with automated procedures on the metric images

#### 4.3 Metric images - Manual measurements

In the point visualization of Figure 5 it is already possible to distinguish the shapes of the folds on the dress. This point cloud is not dense enough (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

[<http://www.geomagic.com>]. The folds of the dress are now well reconstructed and modeled, as shown in Figure 9.

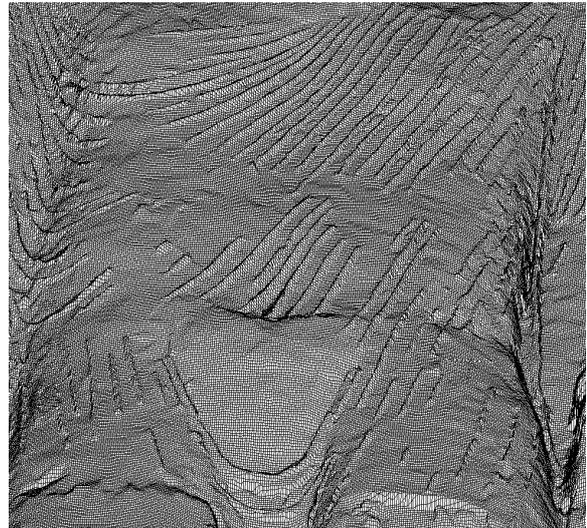


Figure 9: Visualization in wireframe mode of the 3D structures on the central part of the dress of the Buddha

With the commercial software some editing operations of the meshes are also performed:

- holes filling: polygon gaps are filled by constructing triangular structures, respecting the surrounding area;
- noise reduction: spikes are removed with smooth functions;
- edges correction: faces are splitted (divided in two parts), moved to another location or contracted;
- polygons reduction: in some areas, the number of triangles is reduced, preserving the shape of the object.

The final 3D model, displayed in Figure 10, shows also the reconstructed folds of the dress. Compared to Figure 7 this represents a much better result. For photorealistic visualization, the central image of the metric data set is mapped onto the model, as shown in Figure 11.

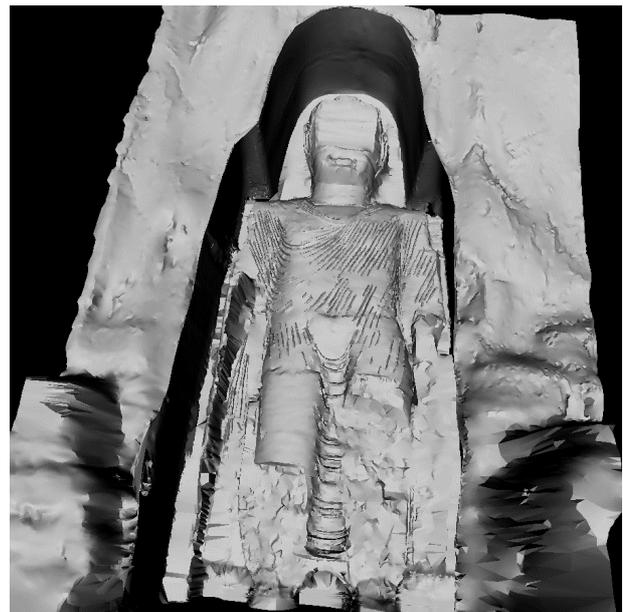


Figure 10: Shaded model of the Buddha, reconstructed with manual measurements on the three metric images

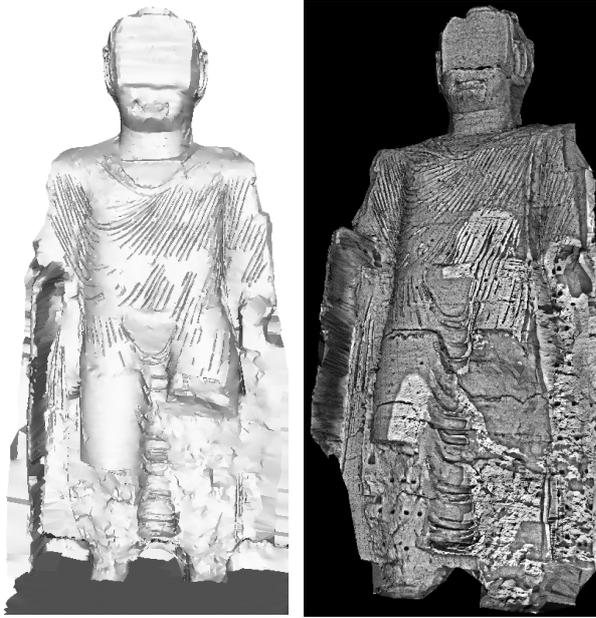


Figure 11: The 3D model of the statue created with manual measurements on the metric images, displayed in shaded (left) and texturized mode (right)

### 5. 3D MODEL VISUALIZATION

Different tools are available to display 3D models, shareware or commercial software, with or without real-time performance, interactive or not.

The generated model can be visualized with a software developed at our Institute and called Disp3D. It allows the visualization of a 3D model as point cloud, in shaded or textured mode, as well as with interactive navigation [Gruen et al., 2001].

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 12).

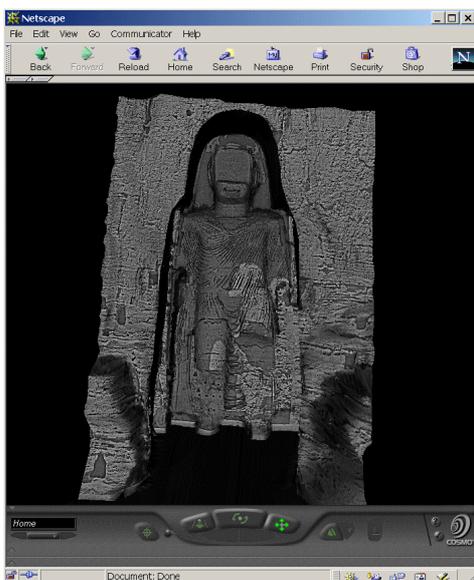


Figure 12: Visualization of the Buddha model with Cosmo Player plug-in in Netscape.

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>. They usually render the model offline, using antialiasing functions and producing portable videos like MPEG or AVI.

Finally, a way to display static view 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 13).

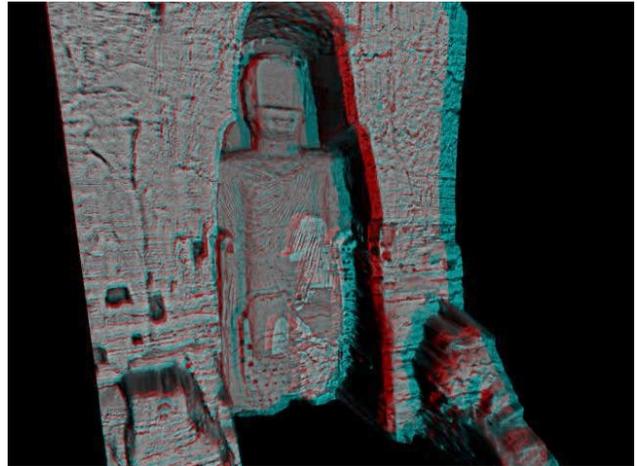


Figure 13: Anaglyph image of the reconstructed 3D model

### 6. PHYSICAL RECONSTRUCTION

The 3D computer model that we reconstructed with the manual procedure is used for a 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). 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.

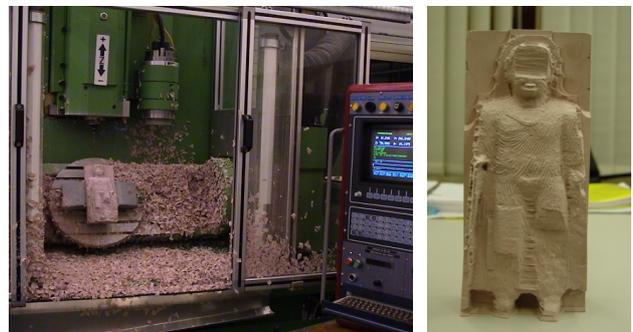


Figure 14: The milling machine used for the physical reconstruction of the Bamiyan Buddha (left) and an image of the model (right).

## 7. 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 automated point cloud generation using four internet images, automated point cloud generation using three metric images and 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 other important edges are missed. 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 situ. The problems encountered 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 conditions of the object, 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. Commercial reverse engineering software could also not generate correct meshes (mainly because the point cloud is not dense enough in some parts) and conventional 2.5D Delauney triangulation was used.

When measurements are done in manual mode it is crucial for the operator to understand the functional behaviour of the subsequently activated 3D modeler. An on-line modeler would be very beneficial, as during the point measurements, the results of this modeler could be directly plotted onto the stereomodel and the operator could control the agreement of the on-line model with the measurements and the structure of the object.

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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