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PHOTOGRAMMETRIC RECONSTRUCTION OF THE GREAT BUDDHA OF BAMIYAN, AFGHANISTAN

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Abstract

In the valley of Bamiyan, Afghanistan, approximately 1700 years ago, two large standing Buddha statues were carved out of the sedimentary rock of the region. They were 53 and 38 m high and the larger one figured as the tallest representation of a standing Buddha in the world. In March 2001 the Taleban government militia demolished the colossal statues. After the destruction a group from ETH Zürich completed the computer reconstruction of the Great Buddha, which can serve as the basis for a physical reconstruction. This paper reports the results of the image-based 3D reconstruction of the statue, performed on three different data-sets in parallel and using different photogrammetric techniques and algorithms.

Keywords: 3D reconstruction, Bamiyan Buddhas, image matching, modelling, orientation, visualisation

The Buddha, the Godhead, resides quite as comfortably in the circuits of a digital computer (or the gears of a cycle transmission) as he does at the top of a mountain or in the petals of a flower. (Robert Pirsig, Zen and the Art of Motorcycle Maintenance, W. Morrow & Company London, 1974, 432 pages)

Introduction

The region of Bamiyan, approximately 200 km north-west of Kabul, Afghanistan, was one of the major Buddhist centres from the 2nd century AD up to the time when Islam entered the area in the 8th 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 (Fig. 1), at an altitude of 2500 m, three big statues of Buddha and a great number of caves were carved out from the sedimentary rock of the region (Figs. 2 and 3). There were two big standing Buddha statues, which stood about 900 m apart, while in the centre there was a smaller image of a seated Buddha (Fig. 5).

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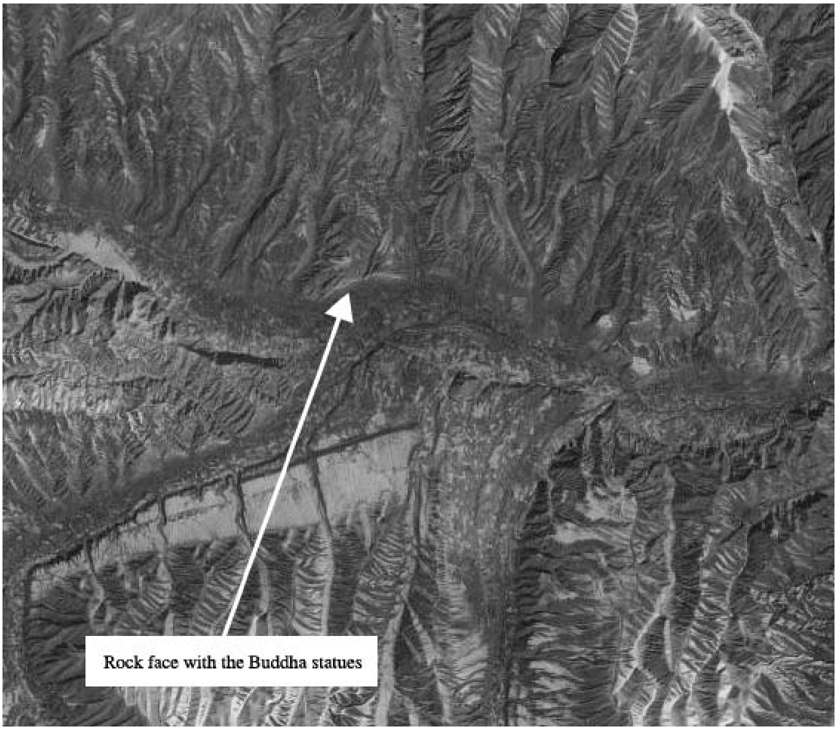

FIG. 1. The Bamiyan valley, as seen by Ikonos
(courtesy of Space Imaging, Inc., Denver, CO (Grant Street)).

The Buddhas were built under the control of the Kushan dynasty, which ruled between the late 1st century and early 3rd century AD over a kingdom incorporating Northern India, certain regions of Central Asia and areas corresponding to present-day Afghanistan and Pakistan. The Emperor Kanishka ordered the construction of the statues and some descendants of Greek artists, who went to Afghanistan with Alexander the Great, started the construction that lasted probably until the 3rd or 4th century AD. The Kushan dynasty produced the distinctive Gandhara art. Gandhara developed an artistic style blending Greco-Roman influences and Indian Buddhism.

> *The Musée National des Arts Asiatiques-Guimet holds many spectacular pieces of art from that period of great artistic refinement (*Musée National des Arts Asiatiques-Guimet, 2004).

These objects of religious sculpture, including the Buddhas of Bamiyan, belong to the Indian Mathura school. J. Hackin even argues that:

> *Nothing could be more natural than that the artists of Mathura were inspired by the statues at Bamiyan justly famous at that time throughout the Buddhist world* (Hackin, 1928: page 109).

The larger statue of Bamiyan was 53 m high while the smaller one measured 38 m (Fig. 3). The Great Buddha should represent Vairocana, the "Light Shining throughout

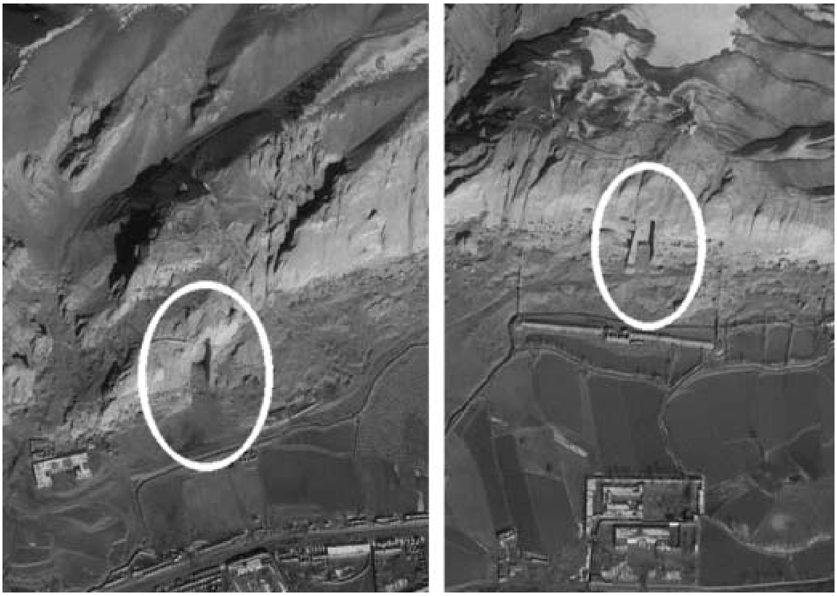

FIG. 2. The empty Buddha caves as observed by Ikonos (courtesy of Space Imaging, Inc.). Left: Great Buddha. Right: Small Buddha.

FIG. 3. The Great Buddha (left and centre) and the smaller statue (right).

the Universe" Buddha, while the small one should represent Shakyamuni (AIIS, 2004; IRAO, 2004). They were cut from the sandstone cliffs and were covered with a mud and straw mixture to model fine details such as the expression of the face, the hands and the folds of the robe. An account of the building technique of the colossal statue is given in Knobloch (2002: page 93):

> *The Bamiyan Buddha was created by cutting a high-relief figure into the face of the soft conglomerate cliff. It is possible that the niche was carved out first, using scaffolding slotted into holes cut into the cliff, before the ambulatory galleries were carved; the scaffolding later being replaced by a*

> *series of permanent wooden ladders, landings and facades. The torso was roughly shaped and detailing of the folds of the gown was built out by cutting lines of shallow holes for wooden pegs on which were hung ropes coated with thick stucco.*

The lower parts of the arms were constructed on wooden armatures while it is generally assumed that 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 and may even be among the first representations of Buddha himself in human form, replacing the older symbolic portrayals of the Indian bas-reliefs. The niches of the statues, as well as most of the caves of the cliff, were also decorated with colourful frescos.

First written reports about the Buddha statues come from the Chinese travellers Fah-Sien (around AD 400) and Hsuan-Tsang (AD 630). Especially, Hsuan-Tsang describes in great detail the site where 5000 monks were active in monasteries and caves, carved into the large rock face, containing also two standing Buddhas. He also reports of the Great Buddha being painted in vivid colours and having a wooden face mask painted in gold.

The first damage came about with the arrival of Islam in the 8th century. Reportedly, Genghis Khan destroyed the town of Bamiyan in 1221, but did not do any harm to the monks and the Buddhas. Major destruction through the firing of cannon balls at the statues is reported under the Moguls Shah Aurangzeb and Nadir Shah in the 17th and 18th centuries, respectively.

The 19th century saw an influx of amateur archaeologists, who more specifically were medical doctors, military personnel, government agents and the occasional traveller. Alexander Burnes, who visited Bamiyan in 1832, is considered the modern discoverer of the Buddhas, although he was not the first eyewitness of modern times. Fig. 4 shows a drawing by Burnes in which the Buddhas have a fantastic appearance and only little resemblance with reality.

FIG. 4. Alexander Burnes' drawing of the Buddhas of Bamiyan.

In 1833 the military deserter, secret service agent and treasure hunter James Lewis (who called himself "Charles Masson") visited the site. It is said that he left the following graffito (which however could not be found by the present authors): "If any fool this high samooch explore know Charles Masson has been here before."

It took another century until the first serious excavations and investigations were conducted. For the French agency DAFA (Delegation Archéologique Française en Afghanistan) renowned experts like A. Godard, J. Carl and J. and R. Hackin worked between 1920 and 1930 in Bamiyan. R. Hackin published the first guidebook on Bamiyan in 1934. He noticed inexperienced craftsmanship on the Small Buddha as well as some cumbersome and primitive features. Since the Great Buddha is more sensibly proportioned, it was assumed that it was built after the Small Buddha. But there is no clear evidence for this.

Robert Byron, the English travel writer who visited Bamiyan in 1933/34 obviously disliked the Buddhas very much. He wrote in his *The Road to Oxiana*:

> *I should not stay long at Bamian. Its art is unfresh … Neither [Buddha] has an artistic value. But one could beat that: it is their negation of sense, the lack of any pride in their monstrous flaccid bulk that sickens.*

But then he went on to marvel about the landscape:

> *The colours of this extraordinary valley with its cliff of rhubarb red, its indigo peaks roofed in glittering snow and its new-sprung corn of harsh electric green, shone doubly brilliant in the clear mountain air … And there suddenly, like an enormous wasps' nest, hung the myriad caves of the Buddhist monks, clustered about the two giant Buddhas.* (Byron, 1981)

Violent events since 1979 have damaged both society and infrastructure in Afghanistan and have greatly reduced the number of visitors to Bamiyan. The long period of conflict culminated in an edict by the Taleban government to destroy non-Islamic images in the country. Despite major international efforts, notably by ICOMOS (2001) and UNESCO, to persuade the government to leave such works of world cultural heritage unharmed, or to accept the building of walls which would leave them merely hidden, the Bamiyan statues were demolished by Taleban forces in March 2001 (Figs. 5 and 6).

The quality of the Buddha statues can no longer be argued about, because they are gone. But the valley of Bamiyan and its surroundings, which we visited on a photogrammetric field campaign in August 2003, is one of the most beautiful sites and spectacular views of this world.

After the destruction, an intensive discussion started at an international level concerning the need for a physical reconstruction of the statues. The matter is not yet resolved, although many recent signs point towards a reconstruction (UNESCO, 2004) (Fig. 6).

ETH Zürich has volunteered to perform the computer reconstruction, which can serve as a basis for the physical reconstruction. In fact, using a computer model, a statue at 1/10 of the original size will first be built and displayed in the Afghanistan Museum in Bubendorf, Switzerland. But the most recent developments actually call for the placement of this model into the National Museum of Kabul, Afghanistan.

Originally, ETH Zürich interest in the reconstruction of the Great Buddha was purely scientific. It was planned to investigate to what extent such an object could be

FIG. 5. A panorama of the cliff of Bamiyan valley after the destruction with three images showing the Buddha statues prior to demolition.

FIG. 6. Left: The explosion of the big statue (courtesy of CNN). Centre: The empty cave after the destruction. Right: The stones of the big statue recovered and protected with UNESCO bags.

reconstructed fully automatically, simply by using amateur images taken from the Internet. The main scientific challenge here lies in the fact that no typical photogrammetric information (such 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, as described later. After learning about the efforts to actually rebuild the Great Buddha it was decided to get involved in that project beyond a purely scientific approach in order to contribute as much as possible to the success of the work through the use of ETH Zürich's technology. Finally, three sets of images were available for the computer reconstruction: Internet images, amateur images from a visiting tourist and metric images. The resulting computer models of the Buddha varied in accordance with the images used in each case. The results extracted from the Internet and tourist images served only for scientific purposes and to test the newly developed matching algorithm. The physical reconstruction will be based on a 3D computer model derived from three metric images. These images were acquired in Bamiyan in 1970 by Professor Kostka, Technical University of Graz (Kostka, 1974). They form the basis for a very precise, reliable and detailed reconstruction with an accuracy of 1 to 2 cm in relative position and with an object resolution of about 5 cm. Manual image measurements had to be applied in order to achieve these values.

In this paper are presented the results of the computer reconstruction of the Great Buddha obtained from different data-sets of images and using different photogrammetric algorithms. For each set, the reconstruction process consists of photo-triangulation (calibration, orientation and bundle adjustment), image coordinate measurement (automatic matching or a manual procedure), point cloud and surface generation, texture mapping and visualisation. From Kostka (1974) a contour plot of the larger statue is also available (20 cm isolines, scale 1:100) and some control points were derived from it for use in the photo-triangulation process.

Available Images of the Great Buddha

The work is based on three different types of imagery, used in parallel:

(1) A set of images acquired from the Internet ("Internet images").
(2) A set of tourist photographs acquired in the valley of Bamiyan between 1965 and 1969 ("Tourist images").
(3) Three metric images acquired in 1970 by Professor Kostka, Technical University of Graz (Kostka, 1974).

Of the 15 images found on the *Internet*, four were selected for processing (Fig. 7): two in front of the big Buddha, one from the left side and one from the right side of the statue. All the others were less suitable for photogrammetric processing because of very low image quality, occlusions or small image scale.

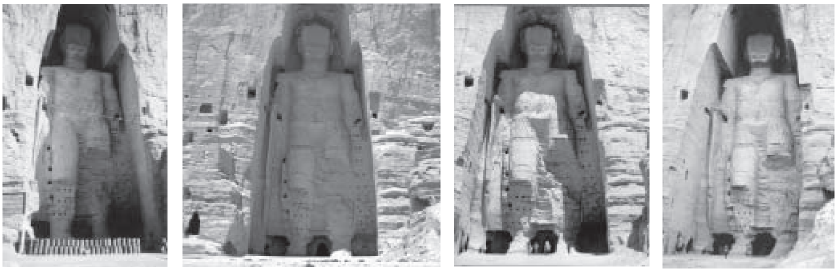

Fig. 7. The Internet images used for the 3D reconstruction.

Fig. 9. The four tourist images (1840 × 1232 pixels) used for the computer reconstruction.

The main problems with these images are their differences in size and scale, the unknown pixel size and camera constants and most of all the different times of acquisition; therefore some parts visible in one image are missing in others (Fig. 8). Also the illumination conditions (shadows) are very different and this can create problems with automatic matching procedures.

The *tourist* images were provided by Harald Baumgartner, who visited the valley of Bamiyan at the end of the 1960s. They were slides, acquired with an Asahi Pentax camera and then scanned at a resolution of 50 μm. Out of 12 available images, four were selected for processing (Fig. 9). Also in this case, the illumination conditions were not constant in all the images and the orientation parameters of the cameras were not known.

The *metric* images were acquired in August 1970 with a TAF camera (Finsterwalder, 1896; Finsterwalder and Hofmann, 1968). The TAF (Terrestrische Ausrüstung Finsterwalder) is a phototheodolite camera (Fig. 16, left) that acquires photos on 13 × 18 cm glass plates. Two fiducial marks are present on the longer sides of the photos while a pointer defines the image horizon with an index that moves vertically.

The original photos were scanned by Vexcel Imaging Inc. Graz, Austria with the ULTRA SCAN 5000 at a resolution of 10 μm. The digitised images each resulted in 16 930 × 12 700 pixels (Fig. 10).

IMAGE MEASUREMENT WITH LEAST SQUARES MATCHING ALGORITHM

A multi-photo geometrically constrained (MPGC) least squares matching software package, developed at the Institute of Geodesy and Photogrammetry at ETH Zürich, was applied to all three image data-sets (Grün et al., 2001, 2003).

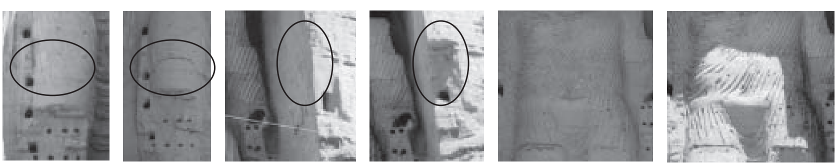

FIG. 8. Changed details between the images (red circles) and different illumination conditions (right).

(a) (b) (c)

FIG. 10. The three metric images acquired in Bamiyan in 1970 by Professor Kostka.

The automatic surface reconstruction (Fig. 11) 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 Förstner operator. At this stage, the master image was subdivided into 7×7 pixel image patches and within each patch only the single feature point which gained the highest interest value was selected. In the implementation, the threshold for the Förstner parameter roundness was set to 0·65 and the grey value variance of the image window was not allowed to drop below 5·0.
(3) For each feature point, using the epipolar geometry determined by phototriangulation, the approximate matches were obtained for the following MPGC matching procedure by standard cross-correlation. The threshold of the normalised correlation coefficient is usually set to 0·7. The position and size of the search areas are determined by using the already known approximate surface model. In order to get this approximate surface, image pyramids and a matching strategy based on region growing, which takes the already measured control points as seed points, are used.
(4) In the final step MPGC matching is applied for fine matching, including patch reshaping parameters (Grün and Baltsavias, 1988; Baltsavias, 1991). MPGC exploits a priori known geometric orientation information to constrain the solution and allows for the simultaneous use of more than two images. The

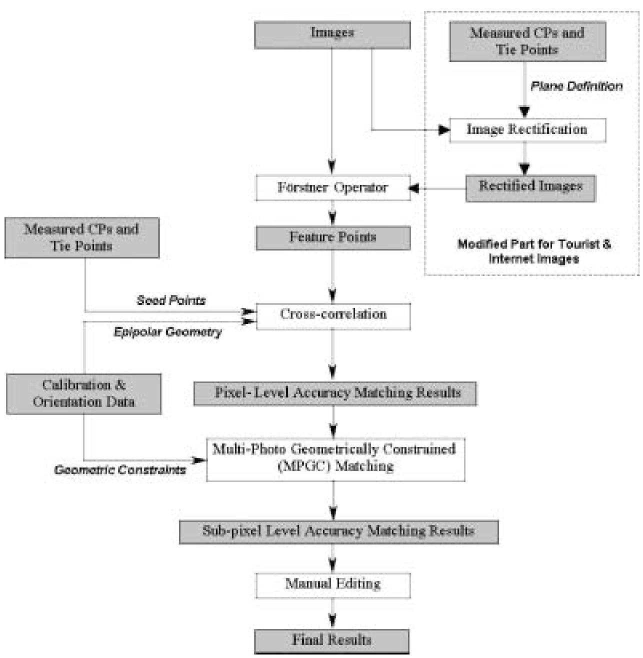

FIG. 11. Data flow diagram of the matching procedure.

algorithm can use blunder and occlusion detection and quality control by self-diagnosis.

MPGC is a non-linear algorithm. Its linearisation requires the procedure to be iterated. Considering the need to speed up the convergence rate, the geometric constraint is usually applied in a fully constrained mode in the first and second iterations. Then the weights of the geometric constraints are decreased in order to consider the errors in orientation data. To reduce the oscillations and divergence problems the reshaping parameters can be constrained according to the image signal content in the image patches and based on the analysis of the covariance matrix of least squares matching.

With the MPGC approach, sub-pixel accuracy matching results and 3D object coordinates can be obtained simultaneously (Fig. 12) and also, through covariance matrix computations, a good basis for quality control.

The matching procedure previously described has also a modified version that is used when the images have large scale and/or rotation differences between each other. In these cases the cross-correlation technique used in the first step to extract the approximations for the MPGC matching normally encounters difficulties. In order to solve these restrictions rectified images are used. The rectified images are generated using a vertical plane fitted to the control and tie points (Fig. 13, left). Then each pixel of the original image is projected onto the vertical plane by using the known orientation parameters. The relationships between the original and rectified images can be calculated using the collinearity equations:

$$X_p = (Z_c - Z_0)\frac{r_{11}x_p + r_{21}y_p - r_{31}f}{r_{13}x_p + r_{23}y_p - r_{33}f} + X_0$$
$$Y_p = (Z_c - Z_0)\frac{r_{12}x_p + r_{22}y_p - r_{32}f}{r_{13}x_p + r_{23}y_p - r_{33}f} + Y_0 \quad (1)$$

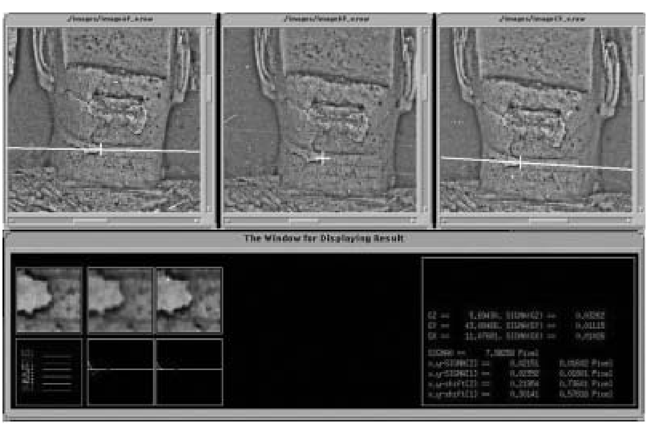

FIG. 12. Epipolar geometry between the metric images to get the correct matching (upper row). MPGC matching results (patch resampling) and computed 3D object coordinates (lower row).

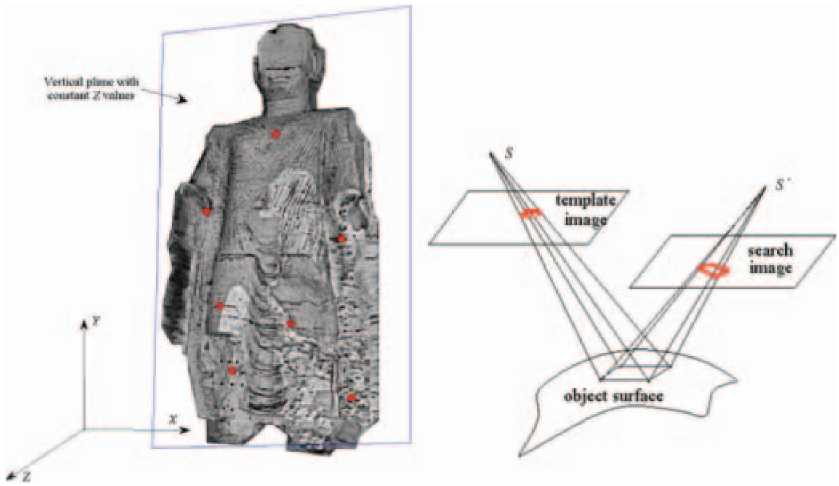

FIG. 13. Definition of the vertical plane with constant Z_c, used for image rectification (left). Calculation of the initial reshaping parameters of MPGC. S, S' are the perspective centres of the template and search image, respectively (right).

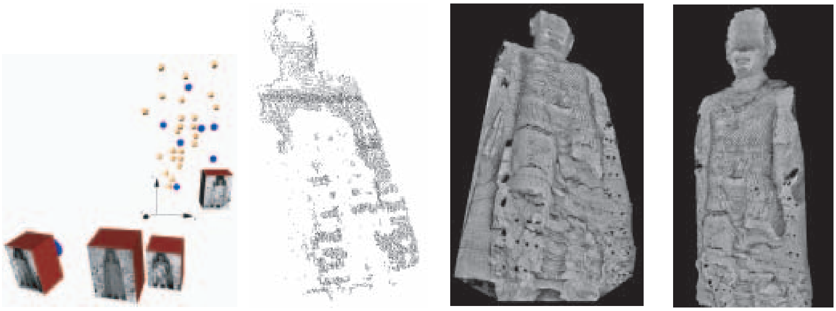

FIG. 14. Recovered camera poses and object coordinates of the Internet images (left). Point cloud (centre) and 3D model of the Buddha displayed in textured mode (right images).

$$
\begin{aligned}
x_p &= -f\frac{r_{11}(X_p - X_0) + r_{12}(Y_p - Y_0) + r_{13}(Z_c - Z_0)}{r_{31}(X_p - X_0) + r_{32}(Y_p - Y_0) + r_{33}(Z_c - Z_0)} \\
y_p &= -f\frac{r_{21}(X_p - X_0) + r_{22}(Y_p - Y_0) + r_{23}(Z_c - Z_0)}{r_{31}(X_p - X_0) + r_{32}(Y_p - Y_0) + r_{33}(Z_c - Z_0)}
\end{aligned}
\qquad (2)
$$

where Z_c is the constant value of the vertical plane; (X_0, Y_0, Z_0) is the position of the perspective centre; $(r_{11}, r_{12}, \ldots, r_{33})$ is the rotation matrix calculated from the attitude values of images; f is the camera constant; and (X_p, Y_p) and (x_p, y_p) are the pixel coordinates of the rectified and original images, respectively. After generation of the rectified images, feature points are extracted in one of them (master image) and their conjugate points in other rectified images are computed by standard cross-correlation and a matching strategy based on region growing. The already measured control and tie points are used as seed points. The threshold of the normalised correlation coefficient is set to a relatively low value (usually 0·7).

The approximate matching results are then refined by MPGC. This procedure is performed on the original images. In order to solve the problems caused by differences in image scales and rotations, the initial values of the reshaping parameters in MPGC matching can be predetermined by using the collinearity conditions for the four corner points of the image patches. The corresponding rays of these four corners in the template image should intersect in object space and their object coordinates can be determined (Fig. 13, right). Through the collinearity equations the corresponding image coordinates in the search image can be determined. The initial values of the four reshaping parameters are determined from these four points and their correspondences.

IMAGE MEASUREMENT WITH VIRTUOZO DIGITAL PHOTOGRAMMETRIC SYSTEM

A commercial photogrammetric package was also tested to recover the 3D model of the Buddha statue. 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 constraints, 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, for example, between two edges. In VirtuoZo, the feature-point-based matching method is first used to compute a relative orientation between the images of a stereopair. Then the measured features are used to weight the smoothness constraints while the approximations found are used in the following global matching method (Zhang et al., 1992).

RESULTS FROM THE INTERNET IMAGES

Photo-triangulation

For every image found on the Internet, the pixel size and a focal length are assumed, as well as the principal point, fixed in the centre of the images. With this last assumption, the size of each image is considered to represent the original dimensions of the photo, whereas in fact it could be just a part of an originally larger image. The assumed pixel sizes are between 0·03 and 0·05 mm.

As no other information is available, an interactive determination of the camera positions was first performed, using a graphical user interface program, also varying the value of the focal length and using some control points measured on Professor Kostka's contour plot. Then these approximations were refined with a single photo spatial resection solution.

The final orientation parameters were then recovered with a bundle adjustment. The image correspondences of the tie points were obtained semi-automatically with adaptive least squares matching (Grün, 1985). The final average standard deviations of the object point coordinates located on the Buddha itself and on its immediate vicinity are $\sigma_{x,y} = 0{\cdot}13$ m and $\sigma_z = 0{\cdot}30$ m. The recovered camera poses and the tie and control points used are shown in Fig. 14, left.

Image Measurement and Surface Reconstruction with the Matching Algorithm

For the surface reconstruction, due to the scale and rotation differences among the images, the modified version of the developed MPGC matching algorithm was applied. A point cloud of approximately 6000 points was obtained. Some gaps are present in the results (Fig. 14, centre) because of surface changes due to the different times 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 Delaunay triangulation is applied, which is clearly sub-optimal. The textured 3D model is shown in Fig. 14, right.

Results from the Tourist Images

Photo-triangulation

The pixel size was provided by Harald Baumgartner who scanned the original images (35 mm film diapositive slides). He also provided three different values of focal length. Therefore, a raw orientation could be performed using some control points measured on Professor Kostka's contour plot and a spatial resection algorithm.

The final orientation parameters were recovered with a bundle adjustment (Fig. 15, left). The final average standard deviations of the object point coordinates located on the Buddha itself and on its immediate vicinity were $\sigma_{x,y} = 0{\cdot}12$ m and $\sigma_z = 0{\cdot}17$ m.

Image Measurement and Surface Reconstruction with the Matching Algorithm

The modified matching procedure on the tourist images resulted in 5585 points. Some blunders were deleted by manual editing and the final point cloud and the related textured model are shown in Fig. 15, centre and right. The relatively low image resolution of the tourist data-set results in a coarse but quite complete 3D model.

Results from the Metric Images

Photo-triangulation

In all TAF images the principal point (PP) is defined as the intersection of the straight line joining the two fiducial 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 (Fig. 16, centre). The focal length of the camera (160·29 mm) is given in Kostka (1974), where the acquisition procedure is also described (Fig. 16, right). The images were acquired in the normal case, with a double baseline and at a distance of about 130 to 150 m from the statue (Fig. 16, right).

Using this information and some control points measured on the contour plot, the first approximations of the exterior orientation were achieved.

FIG. 15. A view of the recovered camera poses of the tourist images (left). Point cloud (centre) and textured 3D model, obtained with ETH Zürich's automated matching program.

With the following bundle adjustment all the parameters of the three images were recovered (Fig. 17); the final standard deviations of the object point coordinates located on the Buddha itself and in its immediate vicinity were $\sigma_{x,y} = 0{\cdot}07$ m and $\sigma_z = 0{\cdot}14$ m. These high values can be explained by the unfavourable control point distribution covering just a small part of the images (see Fig. 14, bigger dots).

Image Measurement and Surface Reconstruction with the Matching Algorithm

The MPGC matching algorithm resulted in fairly reliable and precise results. From the three metric images, 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 Fig. 18 (centre), as well as a textured 3D model (right). Although an automatic blunder and occlusion detection process was used, some blunders are present in the 3D point cloud and they were removed with manual editing. As shown

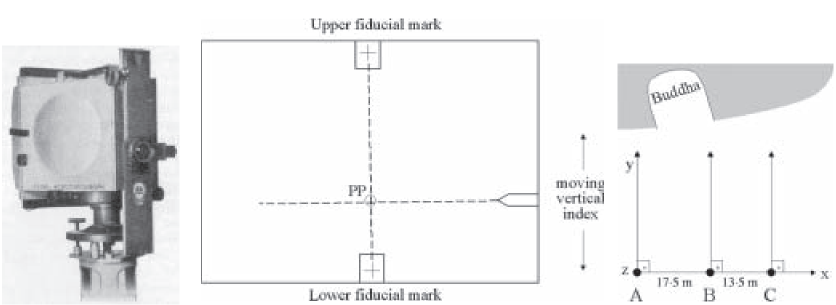

FIG. 16. The TAF camera (left) and the interior orientation of the images (centre). The acquisition geometry of the three metric images as presented in Kostka (1974).

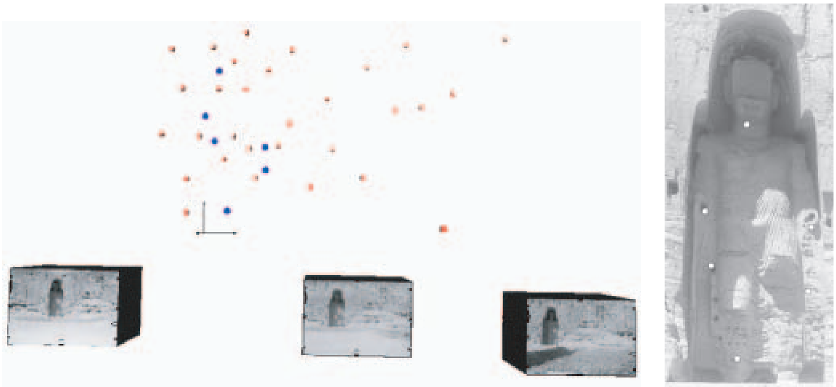

FIG. 17. The positions of the three metric images recovered after the bundle adjustment (left) and the position of the control points on the statue (right).

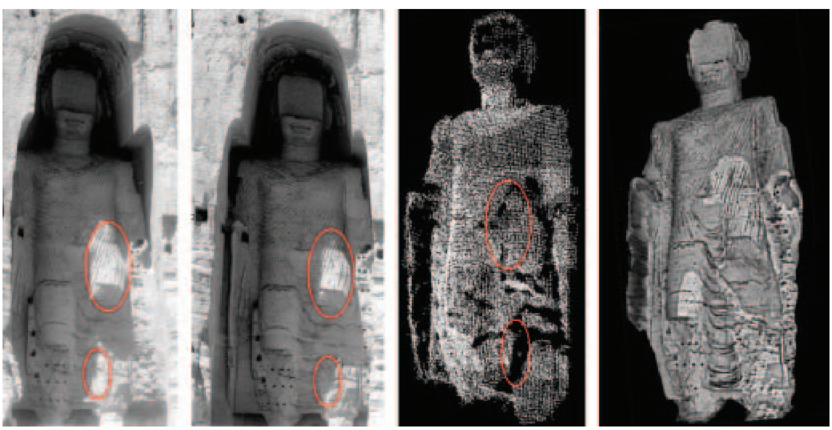

FIG. 18. Left: Two original metric images of the Great Buddha (part). Centre: 3D point cloud generated by automatic matching on the metric images. Right: Textured 3D model.

in Fig. 18, there are some gaps in the point cloud, mainly due to the shading effects caused by the variation of the illumination conditions during the image acquisition (typical areas are marked in Fig. 18).

As shown in Fig. 19, the dress of the Buddha was rich in folds, which were between 5 and 15 cm in width. Many folds could not be exactly reconstructed with the automatic program. Fig. 19 also shows some of the problems that the automated matcher had to deal with: high noise values in the shadow areas, large differences between illuminated and shadow areas, and artefacts (straight lines) from the photographic development process. Other reasons for failure are: the image patches of least squares matching are assumed to correspond to planar object surface patches but, along the folds, this assumption is no longer valid and the small features are smoothed

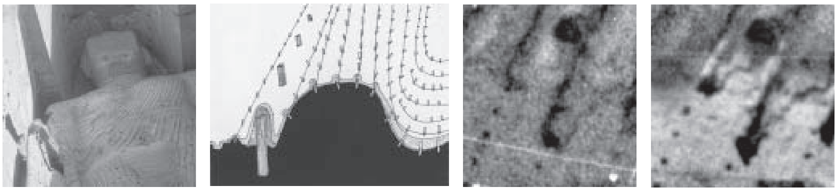

FIG. 19. The folds on the dress that the automated algorithms cannot completely reconstruct (left). Corresponding left and right image patches, showing large differences in image content (right).

out (Fig. 20). Secondly, taking a very small patch size could theoretically avoid or reduce the smoothing effect, but may result in problems with the determination of the reshaping parameters. Fig. 20 compares the cases of small and large patch sizes over the folds of the dress. While a large patch tends to smooth out the local 3D information, a small patch may not include sufficient signal content for the matching. In future work, edge-based matching will also be explored to reconstruct those very small features of the Buddha statue.

In view of these matching problems precise manual measurements were used to reconstruct the exact shape of the dress and other very small features of the statue in order to provide complete data for a future physical reconstruction.

Image Measurement and Surface Reconstruction with a Commercial Package

It was decided to test also the VirtuoZo digital photogrammetric system for comparison. For the matching procedure, see the details already given on the *VirtuoZo system*.

In the application, the metric images of Fig. 10(b) and (c) from Professor Kostka were used to reconstruct the 3D model. A regular image grid with 9 pixels spacing was matched using a patch size of 9×9 pixels and four pyramid levels. As a result, a very dense point cloud of approximately 178 000 points was generated (Fig. 21). The statue as well as the rock around it is well reconstructed, but due to the smoothness constraint

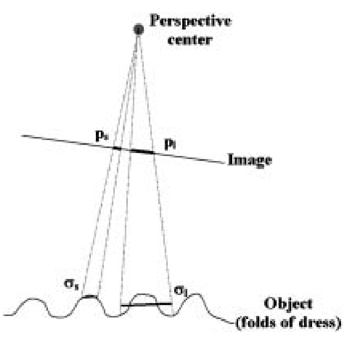

FIG. 20. Patch definition in least squares matching. p_s, p_l represent the image patches (small, large). σ_s, σ_l represent the object planar patches (small, large).

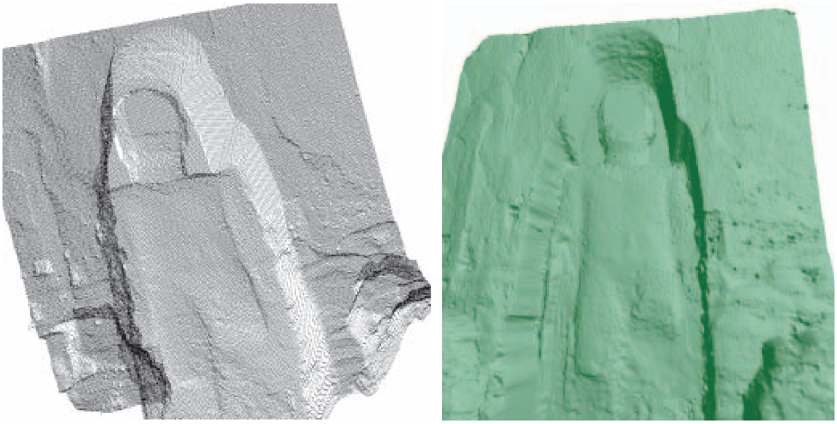

FIG. 21. The Great Buddha generated with VirtuoZo matching on the metric images (left: point cloud, right: shaded model).

and grid-point-based matching the small folds on the body of the Buddha were filtered or skipped and they are not visible. A 2·5D Delaunay triangulation was applied for the surface modelling. Without losing its topology, the 3D surface model of the Buddha was expanded to a plane by transforming the Cartesian coordinate system to a cylindrical coordinate frame. In the defined $\rho\theta\zeta$ cylinder frame, ζ refers to the vertical cylinder axis crossing the model centre and parallel to the original Y axis of the Cartesian object coordinate system; ρ is the Euclidean distance from the surface point to the z axis and θ 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 Fig. 21, right. The shaded model looks "bumpy", mainly due to small measurement errors and inconsistencies in surface modelling.

The central image of the metric data-set was mapped onto the 3D geometric surface to achieve a photorealistic virtual model (Fig. 22). The lower parts of the legs are not completely modelled because in the stereomodel used the legs were not visible.

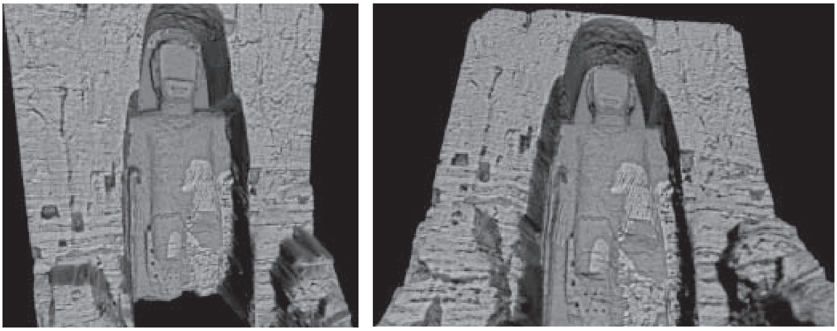

FIG. 22. Visualisation of 3D model of the Great Buddha in textured mode.

Image Measurement and Surface Reconstruction with Manual Measurements

None of the automated procedures presented could recover the small details of the dress, therefore only precise manual measurements could reconstruct the exact shape and curvature of the folds. For this reason, the metric images were imported into the VirtuoZo stereo digitise module (VirtuoZo NT, 1999) and manual stereoscopic measurements were performed. Three stereomodels were set up and points were measured along horizontal profiles at 20 cm intervals, while the folds and the main edges were measured as breaklines.

In the point visualisation of Fig. 23 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 triangulation mesh with commercial reverse engineering software. Therefore, the generation of the surface is performed with the 2·5D Delaunay method, by dividing the measured clouds into separate parts. A mesh is created for each single point cloud and then all the surfaces are merged together with Geomagic Studio software (Geomagic, 2004). The folds of the dress are now well reconstructed and modelled, as shown in Fig. 24.

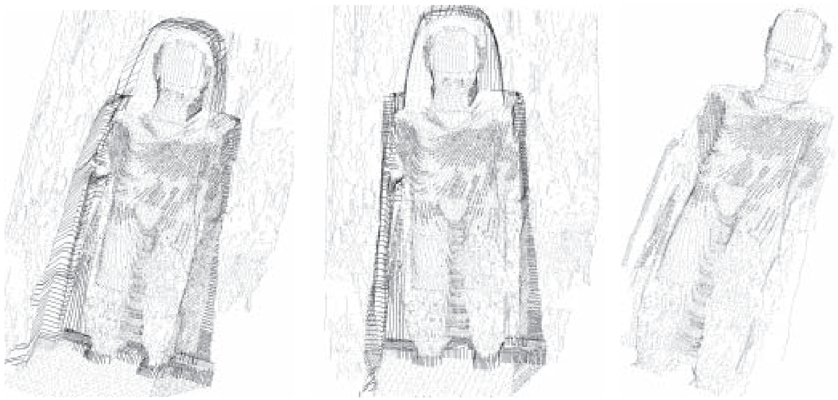

FIG. 23. The point cloud of the manual measurement. The main edges and the structures of the folds, measured as breaklines, are now clearly visible.

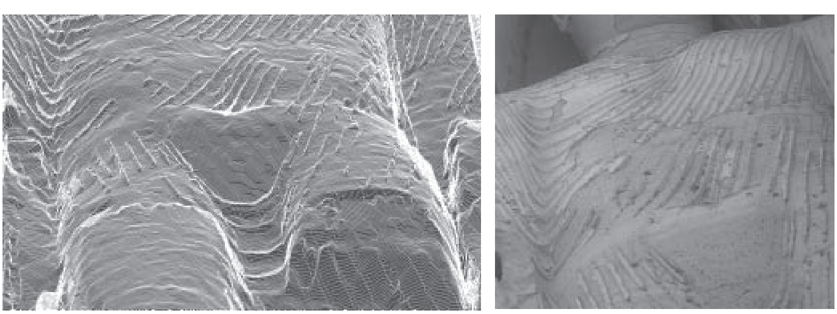

FIG. 24. Visualisation in wireframe mode of the reconstructed 3D structures on the central part of the dress of the Buddha (left). Comparison with the original structures (right).

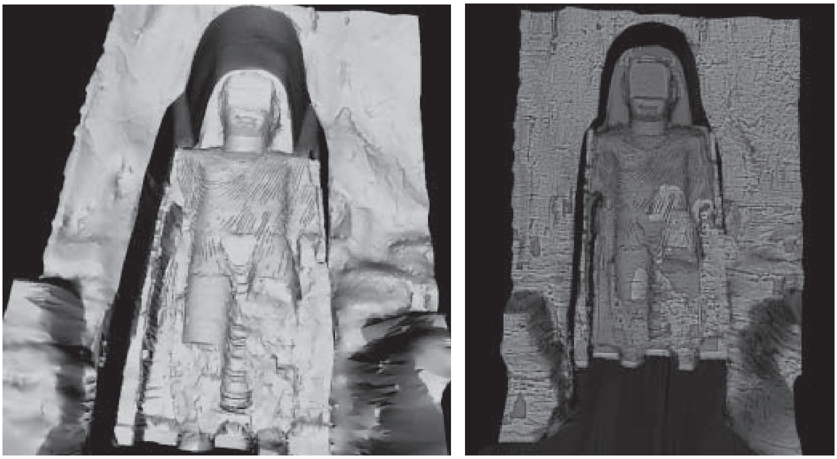

FIG. 25. Shaded model of the Buddha, reconstructed with manual measurements (left) and the related textured 3D model (right).

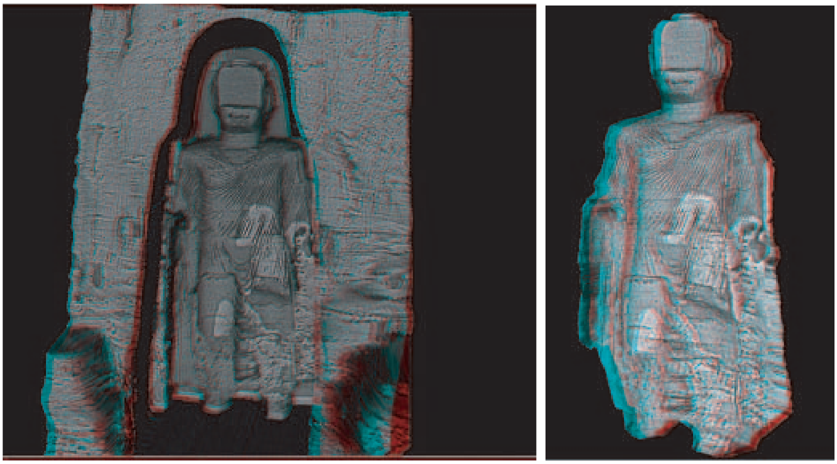

FIG. 26. Anaglyph images of the reconstructed 3D model.

With Geomagic Studio some editing operations on the meshes are also performed:

(a) hole filling: polygon gaps are filled by constructing triangular structures, respecting the surrounding area;
(b) noise reduction: spikes are removed with smoothing functions;
(c) edge correction: faces are split (divided into two parts), moved to another location or contracted;

(d) polygon reduction: in some areas, the number of triangles is reduced, preserving the shape of the object.

The final 3D model, displayed in Fig. 25, shows also the reconstructed folds of the dress. Compared to Fig. 21 (right), this represents a much better result.

For photorealistic visualisation, the central image of the metric data-set is mapped onto the model, as shown in Fig. 25 (right).

3D MODEL VISUALISATION

Many 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 visualised with software developed at ETH Zürich, called Disp3D (Buehrer et al., 2001; Grün et al., 2001). It allows the visualisation of a 3D model as point cloud, in shaded or textured mode, as well as with interactive navigation.

One of the few portable formats to interactively display a 3D model like the reconstructed Buddha statue is VRML. With free packages like Cosmo Player or Vrweb it is possible to display the model and navigate through it or to fly along predefined paths.

Computer animation software (for example, Maya) is generally used to create high quality animations of 3D models. Some examples are presented by ETH Zürich at http://www.photogrammetry.ethz.ch/research/bamiyan/buddha/animations.html. Maya renders the model offline, using anti-aliasing functions and producing portable videos like MPEG or AVI.

Finally, a further way of displaying a static view of 3D models is based on traditional anaglyph images (Fig. 26) in which a stereoscopic view is generated using the complementarity of colours in the RGB channels. The depth information within each model can then be viewed by means of the coloured filter spectacles which may be assumed still to be present in the toolkits of most readers of *The Photogrammetric Record*.

THE PHYSICAL RECONSTRUCTION OF THE GREAT BUDDHA AT 1:200 SCALE

The 3D computer model reconstructed with the manual procedure was used for a physical reconstruction of the Great Buddha (Fig. 27). At the Institute of Machine Tools and Production, ETH Zürich, R. Zanini and J. Wirth have recreated a 1:200 model statue of the Great Buddha (approximately 25 cm high).

For this purpose, the point cloud of the photogrammetric reconstruction was imported to 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 h while the milling of the statue was done in about 8 h.

Conclusions and Future Work

It has been shown that even fairly complex structures can be reconstructed photogrammetrically from Internet images, without any prior knowledge about the geometry of those images. This 3D modelling can be done even automatically with an advanced matching strategy. However, in such reconstructed 3D models essential small features, like the folds of the dress and some important edges, are missed. For the generation of a complete and detailed model, manual photogrammetric measurements are indispensable. Of course they can be performed in stereomodels composed of digital images.

Beyond the issue of measurement, a major problem still exists with the surface modelling. ETH Zürich's own software and commercial modelling software were not satisfactory and finally more time was spent on modelling than on measurement. In order to have a smooth production process the measurement procedure should be adapted to the capabilities of the 3D modeller. This was not the case in the project and this necessarily tighter connection was learned the hard way.

The final 3D model of the Great Buddha can serve as the basis for the physical reconstruction. The most recent developments call for the placement of a 5·3 m high model in the National Museum of Kabul, Afghanistan.

The generation of this computer model concludes the first part of the work on the Bamiyan project. During the last week of August 2003, 4 days were spent in a field campaign on site. Photos were taken with various cameras (Rollei 6006 metric, Sony Cybershot still video) of the complete rock face (more than 1 km in length, up to 100 m high) and of the back-walls of the Buddha caves (to record the situation after the demolition).

An extended 3D model of the site will be produced using SPOT 5 images, including an area of about $11 \times 18\ km^2$ of DTM with Ikonos texture, the rock face at higher resolution and the Buddhas themselves at very high resolution. This requires also the photogrammetric reconstruction of the Small Buddha, which is currently underway. Furthermore, it is planned to reinsert the destroyed frescos into the complex model, using old imagery as well.

Various visualisations and animations are planned, some of them contributing to a 90 min film about "The Great Buddhas", which is planned to be shown in cinemas and on TV in 2005.

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FIG. 27. The milling machine used for the physical reconstruction of the Bamiyan Buddha (left) and an image of the 1:200 model (right).

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Résumé

Il y a presque 1700 ans, dans la vallée de Bamiyan, en Afghanistan, deux grandes statues du Bouddha ont été sculptées dans la roche sédimentaire de la région. Elles étaient hautes de 53 et 38 mètres respectivement; la statue la plus haute était considérée comme la plus grande représentation d'un Bouddha dans le monde entier. En mars 2001 la milice des Talibans a démoli ces statues colossales. Après leur destruction, notre groupe a exécuté une reconstruction a l'ordinateur du grand Bouddha, qui peut servir de base pour sa reconstruction physique. Dans cet article nous décrivons les résultats obtenus avec la reconstruction en trois dimensions (3D) de la statue, sous forme d'images; la reconstruction a été exécutée avec trois différents groupes d'images et en employant différents algorithmes et techniques photogrammétriques.

Zusammenfassung

Im Tal von Bamiyan, Afghanistan, wurden vor ca. 1700 Jahren zwei große Buddhastatuen aus einer längeren Felswand herausgearbeitet, zusammen mit Hunderten von Höhlen und Grotten, welche von buddhistischen Mönchen genutzt wurden. Mit 53 bzw. 38 Metern Höhe zählten diese Statuen zu den größten stehenden Buddhastatuen der Welt. Im März 2001 zerstörten Talibanmilizen die kolossalen Figuren. Nach der Zerstörung führte unsere Gruppe die Computerrekonstruktion des Großen Buddha auf der Basis von früheren Bildern durch. Diese 3D Rekonstruktion kann als Grundlage für eine spätere physische Rekonstruktion benutzt werden.

In diesem Beitrag berichten wir über die Resultate der 3D Rekonstruktion, welche mit drei unterschiedlichen Bilddatensätzen (Amateuraufnahmen und Messbilder) und mit verschiedenen photogrammetrischen Techniken und Algorithmen (manuell und automatisch) durchgeführt wurde.

Resumen

Hace aproximadamente unos 1700 años se excavaron en el valle de Bamiyan, Afganistan, dos grandes esculturas de Buda de pie en la roca sedimentaria propia de la región. Tenían 53 y 38 metros de alto y la mayor era la representación más alta del mundo de una figura de Buda de pie. En marzo de 2001 el gobierno talibán hizo derribar las colosales esculturas. Tras la destrucción nuestro equipo hizo una reconstrucción digital del Gran Buda que puede servir de base para la reconstrucción física. Este artículo describe los resultados de la reconstrucción en 3D de la escultura a partir de tres conjuntos distintos de imágenes, utilizando diferentes técnicas fotogramétricas y algoritmos.

