THE RECONSTRUCTION OF THE GREAT BUDDHA OF BAMIYAN, AFGHANISTAN

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1. Introduction

The region of Bamiyan, ca 200 km North-West of Kabul, Afghanistan (Figure 1), was one of the major Buddhist centres from the second century up to the time that Islam entered the area in the ninth century. For centuries, Bamiyan lay at the heart of the famous Silk Road, offering rest to caravans carrying goods across the area between China and Western Empires. Strategically situated in a central location for travelers from North to South and East to West, the village of Bamiyan was a common meeting place for many ancient cultures. In the Bamiyan valley, at 2700 meters of altitude, three big statues of Buddha and a series of caves were carved out from the sedimentary rock of the region. The Emperor Kanishka ordered the construction of the statues around the second century AD. Some descendants of Greek artists who went to Afghanistan with Alexander the Great started the construction that lasted till the fourth century AD. There were two big standing Buddha statues, which stood about a quarter of a mile apart, while in the center there was a smaller image of a seated Buddha (Figure 2).

The larger statue was 53 metres high while the smaller one measured 35 m (Figure 3). The Great Buddha represents Vairocana, the «Light Shining throughout the Universe» Buddha, while the small one represents Shakyamuni. They were cut from the sandstone cliffs and they were covered with a mud and straw mixture to model the expression of the face, the hands and the folds of the robe. To generate these folds of the dress, cords were draped down onto the body and were attached with wooden pegs (compare Figure 7). The lower parts of their arms were constructed on wooden armatures while the upper parts of the faces were made as wooden masks. The two giants were painted in gold and other colors and they were decorated with dazzling ornaments. They are considered the first series of colossal cult images in Buddhist art. In China, India and Thailand are present many other great representations of the Buddha, as in Leshan, South-West China, where there is the world's largest statue of a Buddha carved in rock: it is a seated Buddha and it measures 71 meters in height and 28 meters in width.

The statues of Bamiyan were demolished on March 2001 by the Taleban, using mortars, dynamite, anti-aircraft weapons and rockets (Figure 4). The Buddhists, the world community, ONU and UNESCO failed to convince the Taleban to leave such works of cultural heritage. The fundamentalist Islamic militia, which has governed most of Afghanistan from 1996 to December 2001, followed an edict of its supreme leader who ordered a campaign of destruction to rid the land of all non-Islamic graven images. The Taleban refused also an offer to build a big wall in front of the statues to cover them and they blasted into dust the two giants. For the Afghanistan militia «... the Buddhas violate the Islamic prohibition against sacred images. They are false idols that must be destroyed. The statues should be destroyed so that they are not worshipped now or in the future ...».

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

Originally our interest in the reconstruction of the Great Buddha was a purely scientific one. We planned to investigate to what extend such an object could be reconstructed fully automatically using just amateur images taken from the Internet. The main scientific challenge here lies in the facts that no typical photogrammetric information (as interior and exterior orientation parameters) about these images is available and that existing automated image analysis techniques will most probably fail under the given circumstances, as described later. After learning about the efforts to actually rebuild the Great Buddha we decided to get involved in that project beyond a purely scientific approach and to contribute as much as we could with our technology to the success of the work.

We generated different versions of the Buddha, depending on which images were used for the computer reconstruction. The results extracted from the Internet images serve only scientific purposes. The actual physical reconstruction will be based on a 3-D computer model derived from three metric images. These images were acquired in Bamiyan in 1970 by

Prof. Kostka, Technical University of Graz [Kostka, 1974]. They form the basis for a very precise, reliable and detailed reconstruction with an accuracy of 1-2 cm in relative position and with an object resolution of about 5 cm. In order to achieve these values we had to apply manual image measurements.

In this paper we mainly present the results of the computer reconstruction. For a more detailed technical description of the digital photogrammetric procedures, in particular the automated reconstruction, we refer to [Gruen et al., 2002].

2. Photogrammetric processing

The photogrammetric process to create a 3-D model from images consists of the following phases:

1. Phototriangulation (calibration and orientation of the images)
2. Image coordinate measurement (automatic matching or manual procedure)
3. Point cloud generation from the measured image coordinates
4. Surface generation (usually denoted as “modeling”)
5. Texture mapping and visualization of the 3-D model.

The three metric images were acquired in August 1970 with a TAF camera (Technische Ausrüstung Finsterwalder [Finsterwalder, Hofmann 1968]). The original photos were scanned by Vexcel Imaging Inc with the ULTRA SCAN 5000 at a resolution of 10 micron. This resulted in digital images of 16930 x 12700 pixels each (Figure 5 - A, B, C).

Using a bundle solution, the interior and exterior orientation parameters of the cameras were computed. The necessary control points were taken from a contour plan 1:100 which had been produced by Prof. Kostka (Kostka, 1974). Figure 6 shows the reconstructed poses of the cameras with the control and tie points for triangulation.

After the establishment of the adjusted image block, the 3-D reconstruction of the statue was realized both with an automatic procedure using our own image matching software, and with manual measurements performed on the commercial Digital Photogrammetric Station Virtuozo [VirtuoZo, 1999].

The automatic procedure was performed to test our newly developed algorithms. However, only the results of the manual measurements will be used for the physical reconstruction of the statue, because only they give the required accuracy and completeness of the model. One reason for the application of manual measurements was that the automated procedures did not give a complete representation of the object. For instance, the dress of the Buddha is rich on folds, which are between 5 and 10 cm in width (Figure 7) and these small features could not be measured automatically with an area-based method of image matching. Only precise manual measurements could reconstruct the exact shape and curvature of the dress and other parts of the statue.

3. Results of the computer reconstruction

With the automatic process we reconstructed the entire Buddha model including parts of the surrounding rocks. A very dense point cloud of 178 000 points was obtained (Figure 8, left). The statue as well as the rock around it are well reconstructed, but the small folds on the body of the Buddha and other details are not visible. Therefore manual measurements are required to exactly reconstruct the curvature of the folds. The central image of the metric data set was mapped onto the 3-D model to achieve a photorealistic virtual model. The result is shown in Figure 8, right.

The manual measurement was executed in profile mode, with horizontal profiles of 20 cm vertical spacing. In addition a large number of object edges were recorded. Thus a point cloud of ca. 28 000 points was obtained. In the visualization of the point cloud of Figure 9 it is now possible to distinguish the shapes of the folds on the robe.

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. In a first step a physical model at scale 1:200 has been produced at the Institute of Machine Tools and Production, ETH Zurich, using a digitally programmed machine tool (Starrag NF100) [Wirth, 2002]. The used material is polyurethane and the machine took about 8 hours to create the model (Figure 10).

5. Conclusions

The photogrammetric reconstruction of the Great Buddha of Bamiyan has been achieved. We have produced various 3-D computer models of different quality, based on automated and manual image measuring techniques. A detailed technical description of the procedures involved can be found in [Gruen et al., 2002]. A web site of the work has also been established on our server and is available at http://www.photogrammetry.ethz.ch/research/bamiyan/, including animations, 3D models and technical details. Following the computer reconstruction, the second phase is concerned with the construction of a 1/10 scale model, which will be set up in the courtyard of the Afghanistan Museum in Bubendorf, Switzerland. As a prerequisite for the third phase of the reconstruction on-site in Bamiyan, the 1/10 scale statue will serve as a study model for the materials to be used, for the construction methods to be applied and for the implementation of the necessary infrastructures. The New7Wonders Foundation in partnership with the Afghanistan Museum in Bubendorf are collecting the funds to finance the project. A large part of the money will go to the stabilization of the cliffs, which were severely damaged by the explosion.

Photogrammetry has proven as the only available technique

that is capable of reconstructing the destroyed Great Buddha at very high accuracy, resolution and completeness.

Modern visualization techniques allow to show the 3-D computer model to a large audience in very appealing forms. From the 3-D surface model any other representation can be derived that may be needed for the physical reconstruction.

Acknowledgement

The authors would like to thank all the people who take part in this project and in particular: Prof. Kostka, Technical University of Graz, for the three metric images; Vexcel Inc. for scanning the metric images; B. Weber, Founder of the New7Wonders Foundation; P.Bucherer, Director of the Afghanistan Museum in Bubendorf, Switzerland; Yuguang Li for the manual measurements on the metric images; Robert Zanini and Joachim Wirth, Institute of Machine Tools Production, ETH Zurich, for the physical reconstruction of the statue at scale 1:200; and finally all the web sites where we found images and other information on the statues.

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Fabio Remondino is currently a PhD student at the Institute of Geodesy and Photogrammetry at the Swiss Federal Institute of Technology (ETH) in Zurich. The topic of his work is 'Character Animation and Understanding from Sequences of Images'. He graduated in Environmental Engeneering at the T.U. of Milan, where he also worked as assistent in the Department of Topography and Geodesy. His main interests are: image sequences analisys, 3D objects reconstruction, Camera calibration. Currently he is also working as webmaster of the International Society of Photogrammetry and Remote Sensing (ISPRS).

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Figure 1:
Afghanistan map

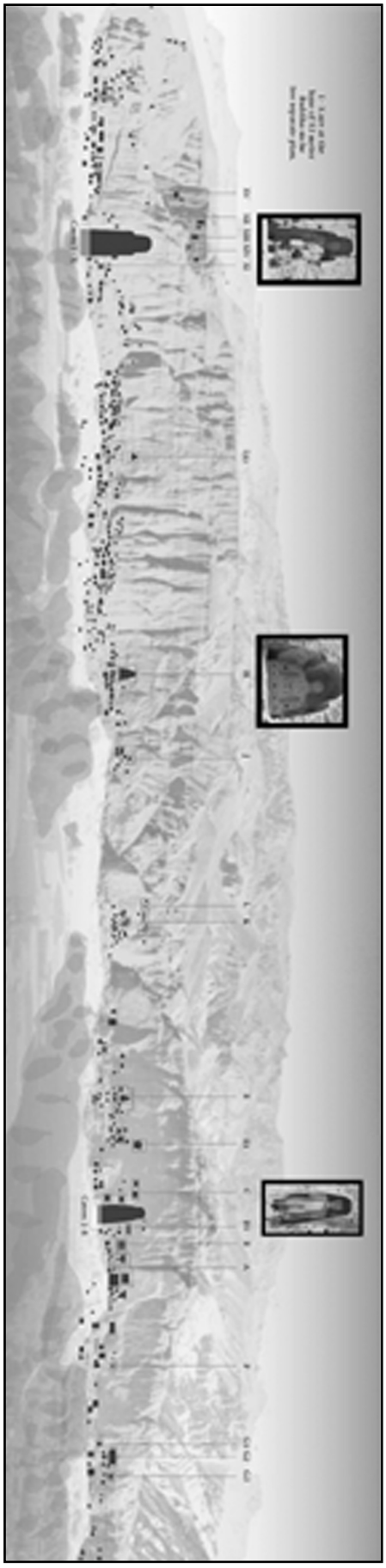

Figure 2: The cliff of Bamiyan valley with the three Buddha statues and the caves

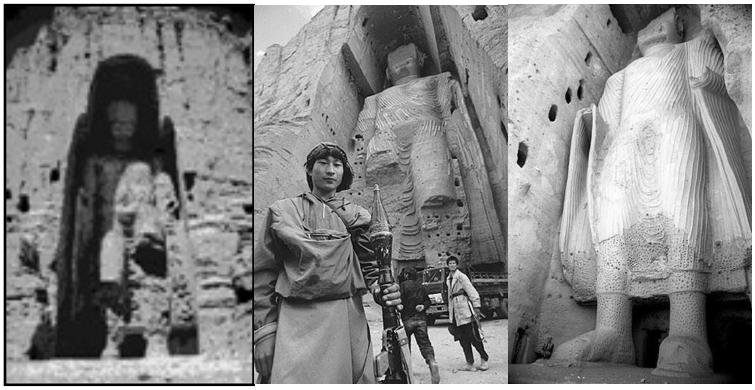

Figure 3: The Great Buddha (left) and the smaller statue (right)

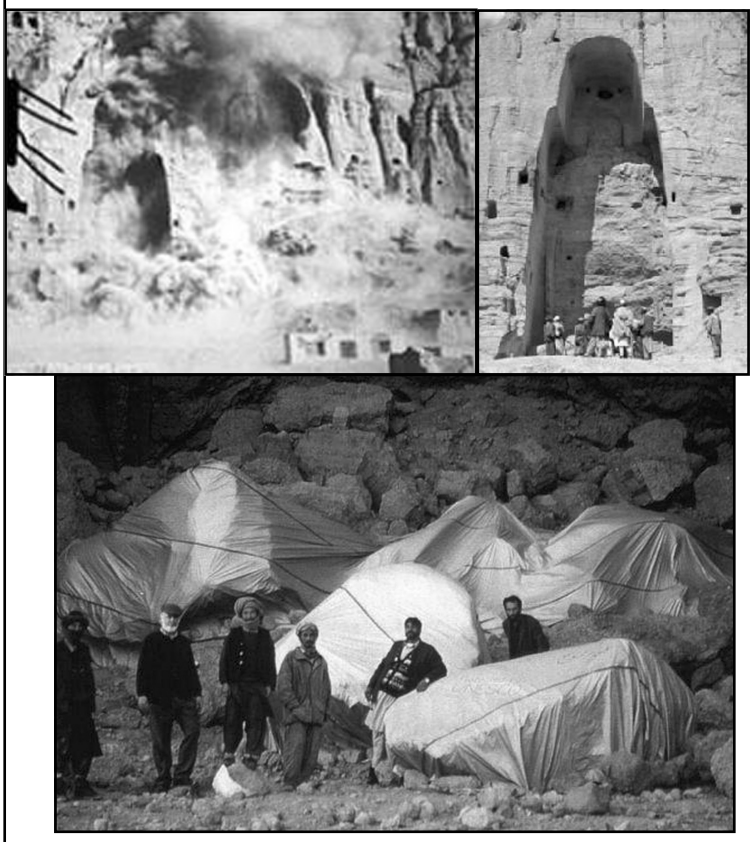

Figure 4: The explosion of the big statue (up left). The empty cave after the destruction (up right). The stones of the big statue recovered and protected with UNESCO bags (down).

Figure 5: The three metric images acquired in Bamiyan in 1970 by Prof. Kostka (A, B, C)

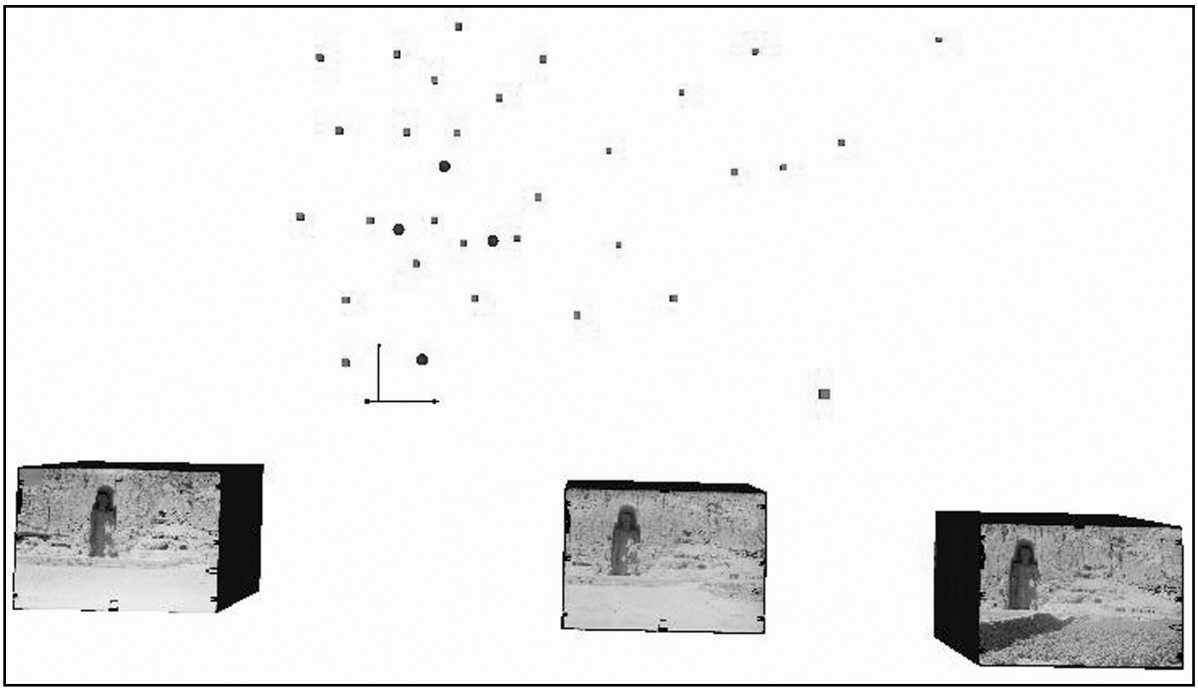

Figure 6: A view on the recovered camera poses of the metric images with tie and control points (red cubes and blue spheres respectively)

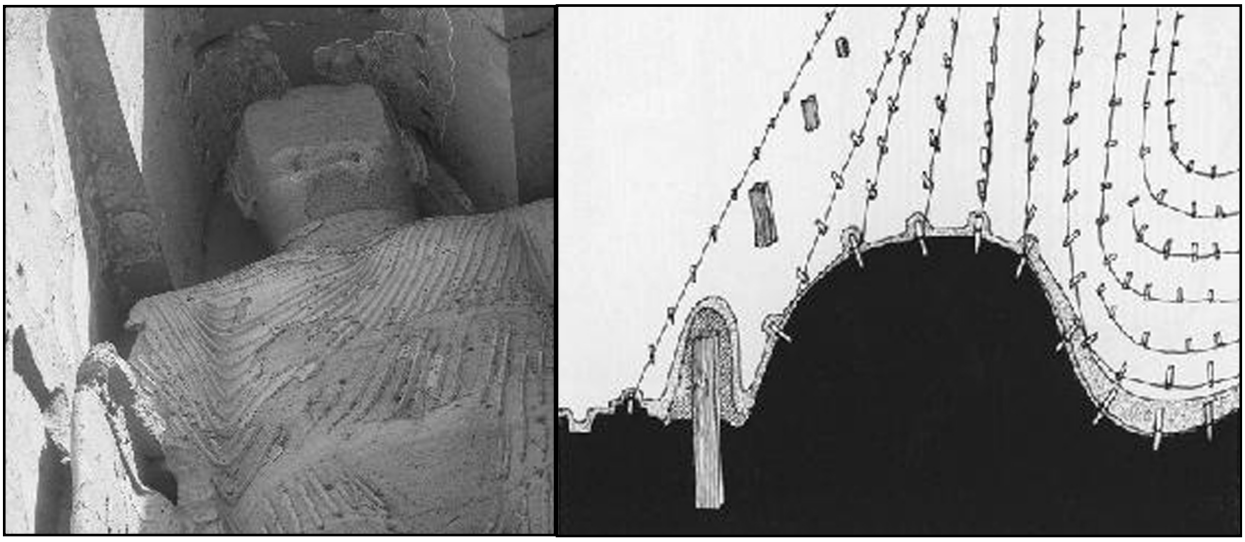

Figure 7: The folds on the dress of the Buddha had to be reconstructed with manual measurements

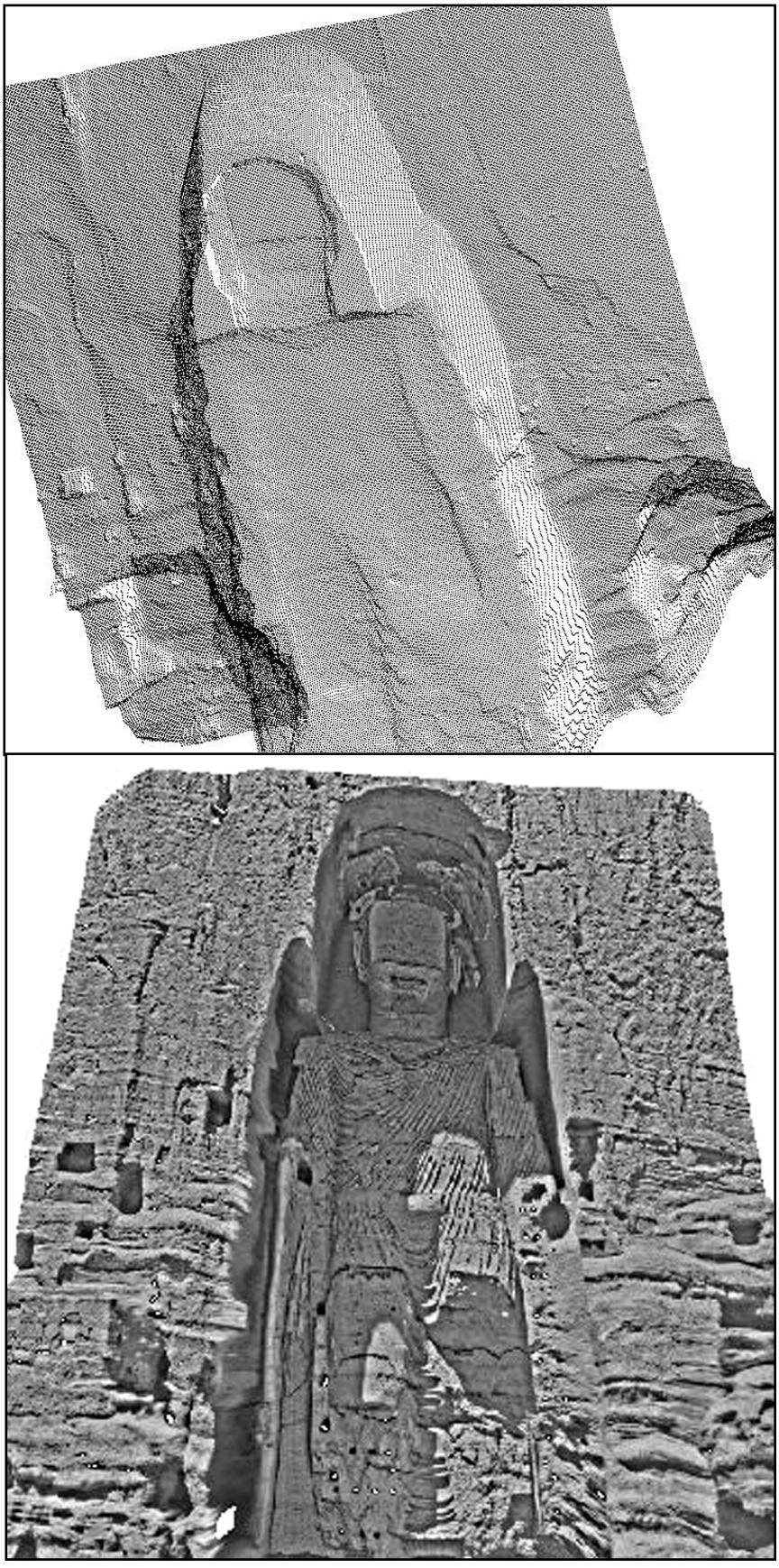

Figure 8: 3-D point cloud generated with an automatic process on the metric images (up).
The detailed folds of the robe are not modeled. The associated photorealistic virtual model (down).

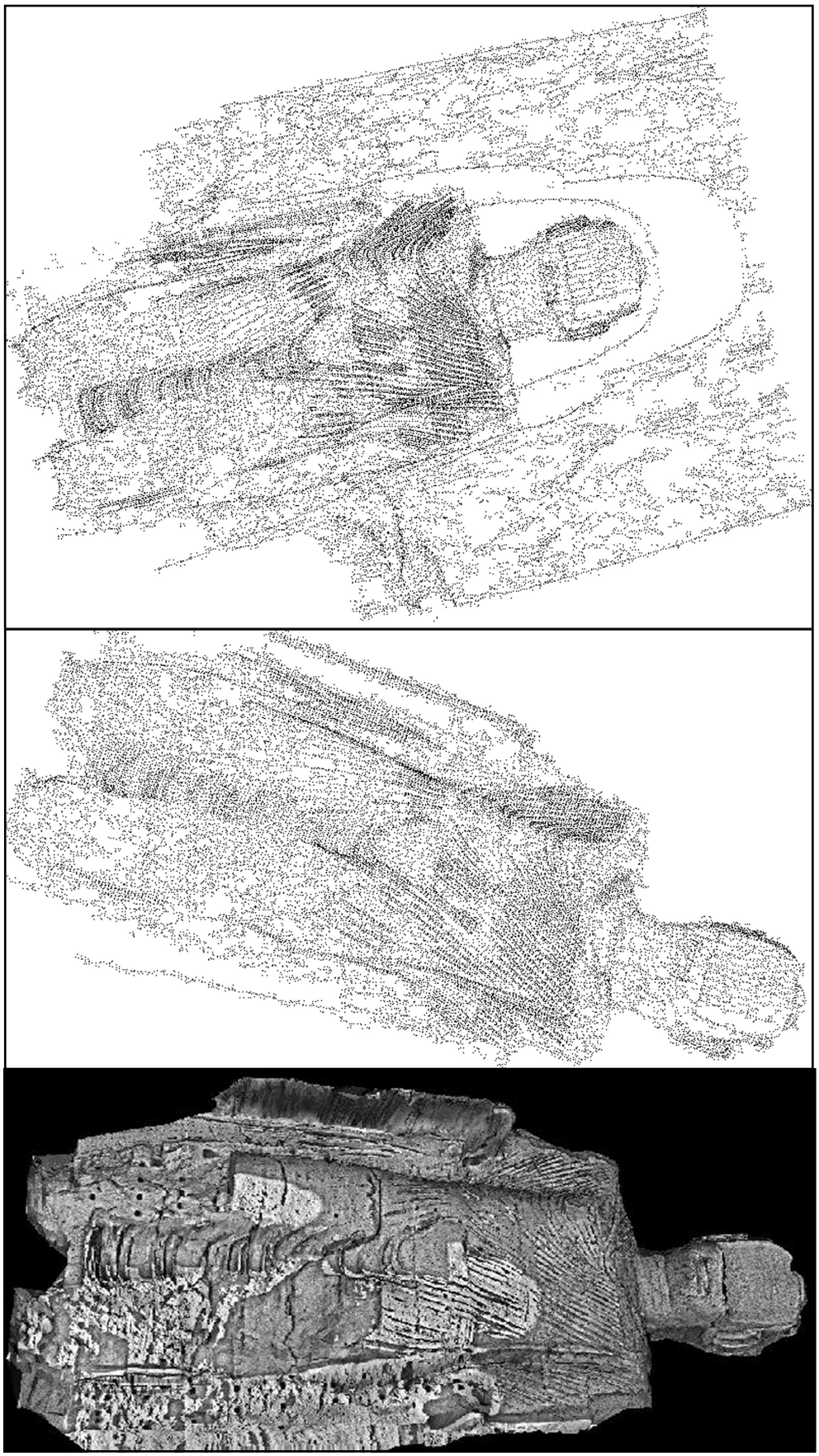

Figure 9: The point cloud of the manual measurement. The main edges and the structures of the folds are well visible (left and central). The texturized 3-D model (right).