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UAV[1] Photogrammetry Project Drapham Dzong, Bhutan

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Introduction

This project is part of the «Bhutan-Swiss Archaeology Project» which was presented in the SLSA annual reports of 2007 and 2008 (Dorji et al. 2009, Meyer 2009, see also Meyer, this volume).

The UAV (Unmanned Aerial Vehicle) photogrammetry project, conducted and funded by the ETH Zurich, is also financed by the «Institut für Bauwissenschaftliche Forschung, Stiftung Kollbrunner/Rodio», Zurich, and further supported by the SLSA. The highresolution stereomodel of the GeoEye satellite, used for modeling the terrain around Drapham Dzong, was donated by the German Aerospace Center (DLR).

During the first archaeological excavation season at Drapham Dzong in autumn 2008 it became clear that the entire ruin is by far more spacious than initially expected (see Meyer 2009). After extensive forest clearance, the outer baileys became clearly visible, both in the north and in the south of the central hilltop citadel with its solid main tower (the so-called *Utze*). These newly discovered structures are enclosed by massive defensive stonewalls and exposed watchtowers in the corners. Alltogether, the architectural hilltop area turned out to be more than twice as large as expected the year before. Furthermore, two steep staircases, fortified by thick stonewalls and turreted in some corners, meander down and lead to the castle's putative economic center on the eastern foot of the rocky hill. Adjacent to a creek, one of these building complexes most probably served as a water-powered mill. This area, too, is enclosed by thick stonewalls and defensive trenches.

Taking into account the considerable size of both the hilltop area (approximately 6500 m^2) and the corresponding building complex on the foot of the hill (approximately 2500 m^2), the complexity of the elaborated staircases connecting these two areas, and the altitude difference of about 75 m, it becomes obvious that surveying and mapping of the whole architectural complex cannot be conducted efficiently by means of conventional terrestrial surveying techniques. Moreover, in the course of the so-called *Spatial Turn* (the (re)discovery of the importance of space and spatiality in the field of social sciences in the 1980ies (see e.g. Döring and Thielmann 2008)) landscape has turned out to be a considerable object of investigation in modern archaeology (David and Thomas 2008). On the one hand, meticulous hand drawings and measurements of construction details give information about construction techniques, handcrafts, and the building history (see Meyer 2009). On the other hand, the acquisition of the whole architectural complex, including its topographical environment, will shed light on its original social function.

A detailed digital three-dimensional mapping of the topography and the remaining structures as discussed here enables the intended analysis of potential cultural acts in which Drapham Dzong once had its function. With a large and detailed landscape model for example, on the basis of the so-called *Least-Cost-Analysis* (see Tobler 1993, Fux et al. 2009) potential mule track routes between Assam in the south and Tibet in the north can then be possibly detected.

Thus, a surveying expedition to Drapham Dzong was planned by our multidisciplinary team. The goal of our expedition in November 2009 was the generation of the prerequisites to produce a 3D model of the excavation site and its immediate surroundings. For this purpose our main surveying device was a model helicopter (to be precise a «quadrocopter») for the acquisition of very large scale aerial images

1 UAV = Unmanned Aerial Vehicle.

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Fig. 1 The archaeological site Drapham Dzong in the upper Choekhor valley of the Bumthang region after forest clearance in autumn 2009. The photo was taken from the eastern hillside. The hilltop citadel in the center as well as the outer baileys on the left and on the right are well recognizable. On the hill's lower left slope one of the fortified steep staircases is visible.

of the site. These images are the basis for photogrammetric measurements and 3D modeling.

Generally speaking, photogrammetry is an indirect measurement technique which derives from images of an object the object itself with its location, shape and size. The images have to be taken in such a manner from different viewpoints that they overlap each other sufficiently well in their object coverage. The images can then be processed on the basis of known camera and lens parameters. By means of the definition of specific object points visible in several images taken from different points of view, the object's geometry can subsequently be calculated by the use of special photogrammetry software. In the following, the fieldworks conducted in autumn 2009 at Drapham Dzong as well as the ongoing photogrammetric data processing for the purpose of 3D modeling are discussed.

Fieldworks

Preparation

Taking into account the considerable size of the object under investigation as well as the complex topography, the modeling with the help of aerial images is most efficient. However, since standard aerial images were not available for this area we had to use highresolution satellite images for the modeling of the wider environment and aerial images taken from a UAV (quadrocopter) for the excavation site modeling. One has to cope with the following factors: The UAV had to be able to carry a digital still video camera at an altitude of more than 3000 m a.s.l. and the equipment had to be easily transportable from Switzerland to Bhutan and carried to the archaeologists' camp far away from the dirt road.

Considering these factors we opted for a special kind of mini-UAV (Unmanned Aerial Vehicle), a so-called quadrocopter, i.e. a UAV with four rotors (see Fig. 4). Quadrocopters are usually light weight systems, which normally have a maximum take-

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Fig. 2 GPS measurement of a ground control point (GCP).

Fig. 3 Overview of the site Drapham Dzong. Image mosaic generated using 5 images taken from the quadrocopter at 120 m above the hilltop.

off weight of up to 5 kg. These systems have a size of 0.5–2 m and they are powered by four electro-motors. Several commercial systems are available on the market. Due to the weight limitations, these systems are highly dependent on wind conditions. Moreover, most of the systems can only fly in the manual or assisted flight modes. In the last years, some systems were upgraded by a flight control system, allowing an autonomous flight with a predefined flight path (Eisenbeiss 2009).

For our field campaign at Drapham Dzong the quadrocopter UAV md4–200 of the company microdrones (microdrones 2010) was chosen, since a previous flight test at the Jungfraujoch (Switzerland) at 3,470 m a.s.l. in autumn 2009 had shown that the system is appropriate for flights at this altitude. The system is equipped with a GPS receiver for self-positioning. The camera we selected was a Panasonic Lumix FX35 with a zoom lens.

For the measurement of ground control points (GCPs), we selected two GNSS (Global Navigation Satellite System) receivers GPS 500 (Leica-Geosystems 2010). One of them was used as a reference station and the second in a mobile mode for the individual measurements of the GCPs (see Fig. 2). For the terrestrial image acquisition, such as for the texture of the vertical walls and the documentation of the field work, Nikon D2Xs and D3X, and a Sony DSC-HX1 still video cameras were used.

Photogrammetric Flights

The size of our area of interest was about 150 m × 300 m. The surface is comprised of moderately sloping areas on the top of the hill and steep rocky flanks which were partly deforested (see Fig. 1 and Fig. 3). The resolution of the images (GSD – Ground Sample Distance, also called «pixel size») was chosen at 5 cm.

The images of the Panasonic Lumix FX35 compact camera have a maximum image size of 3648 × 2736 pixels, with a pixel size of 1.6 microns. Additionally, the camera features an integrated image stabilizer, a shutter speed of up to two milliseconds, and a live-view video function. The camera was calibrated at the Institute of Geodesy and Photogrammetry, ETH Zurich, using the software package iWitness (iWitness 2010) which allows an automated camera calibration using color-coded targets.

For the georeferencing of the images we temporarily placed 11 signalized GCPs (7 on the top of the hill and 4 in the building complex area on its base). These GCPs were constructed as a white paper disc, placed on top of a black background and fixed using a metal bushing and a nail (see Fig. 2). Their position was measured using the static GNSS measurement system GPS 500 (see Fig. 2). After a measurement time of 8 hours totally, an accuracy of 1–2 cm resulted.

First, we had to generate an overview image in which all obstacles of the flight are identifiable (Fig. 3). Then, we roughly rectified this image on the basis of our measured GCPs. Subsequently, the rectified image was loaded into the software mdCock-

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Fig. 4 The Quadrocopter MD4-200 flying at Drapham Dzong during the data acquisition.

pit (microdrones 2010) which allowed both the calculation of image acquisition points and the setting of waypoint attributes in our self-developed flight-planning tool (Eisenbeiss 2009).

Since the autonomous flight modus was not working during the data acquisition, all images were finally acquired in the GPS-based assisted flight modus. Image overlapping was controlled by the operator via the live-view modus of the ground control station. During a flight time of about 25 minutes in total, two image lines above the central part of the site could be flown. However, due to technical problems, it was not possible to acquire UAV-images of the building complexes on the eastern foot of the rocky hill adjacent to the creek. Thus, this part of the site was documented with terrestrial images taken from the hill slope (2 hours of image acquisition).

Photogrammetric 3D Modeling

In this project we had to cope with three types of images:

— High-resolution satellite images for modeling a larger area around the Drapham Dzong hill
— UAV images for modeling the Drapham Dzong excavation site
— Terrestrial images for modeling of other, non-excavated structures at the foot of the hill

These datasets were treated separately. Although the processing of these different types of images follows the same basic principles, the detailed procedures and the used software packages may differ from each other significantly. The individual models thus derived have to be merged and visualized which poses another class of problems.

Here is not the space to describe the modeling procedures in detail. Overviews, including flowcharts for the individual processing steps, and also more detailed procedural explanations, are given in Gruen 2009a, 2009b.

Modeling Drapham Dzong from UAV images

The data processing of the UAV images consists of the following steps:

1. Calibration of the UAV camera
2. Image enhancement. Improvement of the radiometric quality of the UAV images
3. Accurate orientation (georeferencing) of the images
4. Generation of a Digital Terrain Model (DTM)

5. Measurement and modeling of the man-made (excavated) objects (primarily walls, floors, stairs, etc.)
6. Mapping of image texture onto the DTM and the man-made objects

The camera calibration, which can be done either in the office or in the field, gives us the exact values of the camera's and the lens' geometric parameters like camera constant, the coordinates of the principal point, and additional parameters for the correction of the systematic errors introduced by its lens system.

Using the criteria *image sharpness, orientation,* and *overlapping areas,* we selected a subset for further processing from the whole set of images. This enabled us to obtain two image strips consisting of 8 and 10 images respectively which cover the whole hill, including Drapham Dzong's main building structures. Using the Adobe Photoshop software, the images were enhanced in a manner that effects like overexposure were reduced, and both image contrast and brightness were improved.

After image selection and editing, the UAV images were further processed using the Leica Photogrammetry Suite software (LPS; Leica-Geosystems 2010).

For georeferencing we measured in both image strips equally distributed tie points (i.e. significant and static features recognizable in overlapping areas of two or more images) in order to connect (to «tie») the individual images to each other computationally. Only a few tie points were measured manually which could then be used as initial data for the automated tie point generation. The accurate georeferencing of the images, also called «exterior orientation», is a prerequisite for the generation of final products like DTMs, ortho-images or photorealistic 3D models. For this georeferencing, GCPs (ground control points) are also needed. They give information as to how the images (and finally the whole models) are located in an external world coordinate system. In our case, this can either be Bhutan's official surveying/mapping system or the worldwide UTM system. We selected UTM Zone 46 North. The computational procedure of this whole process is called «bundle adjustment».

Then, stereoscopic measurements of the DTM and the building walls were conducted. This procedure was accomplished using LPS and PhotoModeler (Photomodeler 2010). As additional tools, a stereo screen and stereo glasses were required. Finally, the DTM and the top of the measured walls were textured using the UAV images and our own software. Extraterrestrial images were acquired during our field campaign for the texturing of the vertical walls.

Modeling the building structures at the foot of the hill from terrestrial images

The building complexes on the eastern foot of the hill – Drapham Dzong's putative economic center – were documented by means of terrestrial images, partly because our UAV did not record these areas, partly because the aerial views were obstructed anyway by trees and bushes. The area mainly consists of two building complexes on different height levels. The larger building complex is located adjacent to the castle hill, whereas the second one is slightly smaller and is located below, next to a creek. Due to topographical complexity and occlusions by vegetation, the pictures had to be taken from irregular positions which complicated the data processing.

For the terrestrial image acquisition we used two calibrated Nikon still video cameras, D3X and D2XS. The terrestrial images feature a maximal image format of 6048 × 4032 pixels.

The preparation of the terrestrial images was similar to that applied to the UAV images. First, we selected 21 out of totally 95 images for the photogrammetric processing. Since the two building complexes are situated on different height levels and therefore difficult to overlook in combination, we decided to handle two separate image blocks and then stitch them together via control points. For this reason, we split the chosen images into two different groups. The first group consists of 14 images which describe the larger object closer to the hill while the second group contains 7 images of the smaller object.

For the photogrammetric processing of the terrestrial images, we chose the software PhotoModeler (Photomodeler 2010). The image orientation workflow is similar as with LPS, but due to occlusions by the dense vegetation, tie points could not be measured automatically.

The manual measurement of tie points was more difficult than in the UAV images. Due to a smaller number of well-visible walls and thus well-defined points, stones and stumps had to be used as tie points. Since not enough GCPs were available in this area, it was not possible to directly calculate the orientation from this set of images. We solved this problem via the calculation of eccentric ground control points by using points from the other oriented image block.

Once the processing of the terrestrial images was done, we proceeded with modeling the object structures. The first part of this step was realized using PhotoModeler. In that part, we measured points along the top edge of all walls which are visible in the pictures. Thereby, each point was measured in at least two images. Since some walls were obscured by trees, it was not possible to detect all structures in great detail. Also, in order to model the environment of the structures, it was necessary to measure further points on the ground. These had to be measured in at least two different images as well. From these points, we generated a DTM by means of interpolation. The second part of the modeling was the reconstruction of the walls with the program CyberCity Modeler (Cybercity 3D 2010). CyberCity Modeler connects all points of the top wall edges and generates a consistent 3D surface model. The results are the upper surfaces of the walls. In the next step, the borders of these surfaces were extruded vertically and intersected with the DTM. The result was a 3D model of the eastern part of the excavation (see Fig. 5). Due to many occlusions, texture mapping is very demanding and will be performed at a later date.

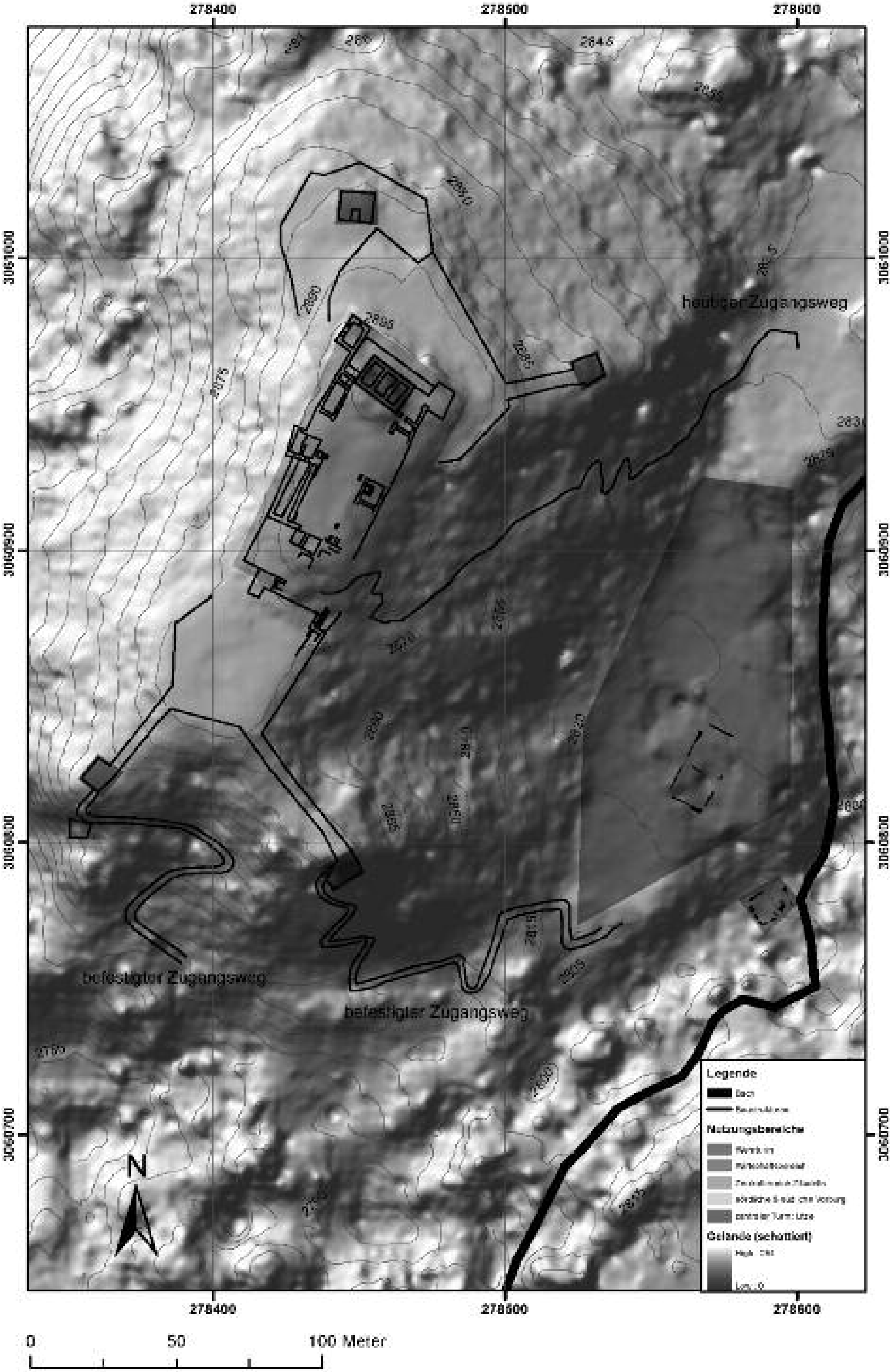
The models derived from these images will also be integrated into the models generated from the UAV and satellite images at a later date.

Fig. 5 Map showing the hilltop complex and the lower building remains at the foot of the hill. The ruins were photogrammetrically mapped from UAV images, the Digital Surface Model and the contour lines were generated from GeoEye-1 satellite imagery using the software SAT-PP.

Generation of a larger area DSM and ortho-image from GeoEye-1 satellite imagery

In order to visualize the larger topographic context of Drapham Dzong, a Digital Surface Model (DSM) covering an area of 10.7 × 10.7 square kilometres was generated using two GeoEye-1 stereo images with 0.50 cm ground pixel size (GSD) in PAN mode. The orientation of these two images was already given by Rational Polynomial Coefficients (RPC) which were provided with the images by the German Aerospace Center (DLR). For the purpose of automated DSM generation, we used the SAT-PP software which was developed at the group of Photogrammetry and Remote Sensing at ETH Zurich. The image matching algorithm and its implementation is described in detail in the scientific literature (Zhang 2005). Therefore, it is only briefly mentioned here. The software is designed to measure identical points in overlapping images acquired from different positions by means of a complex algorithm that matches interest and grid points and also edges. Furthermore, geometrical constraints are applied in order to increase the reliability and accuracy of the measurements. The result is a dense dataset of 3D points and edges which, finally, are combined into a raster dataset that represents the shape of the terrain covered by the stereo scenes. The underlying algorithm has proved to be one of the most accurate automatic methods for DSM generation worldwide.

After the DSM was generated, it was used for the generation of an ortho-image using the PAN channel with 0.50 m ground resolution and the red, green and blue channels (1.61 m resolution) of the GeoEye-1 imagery. The resulting ortho-rectified channels were then combined into a RGB image by means of pan-sharpening using the Brovey-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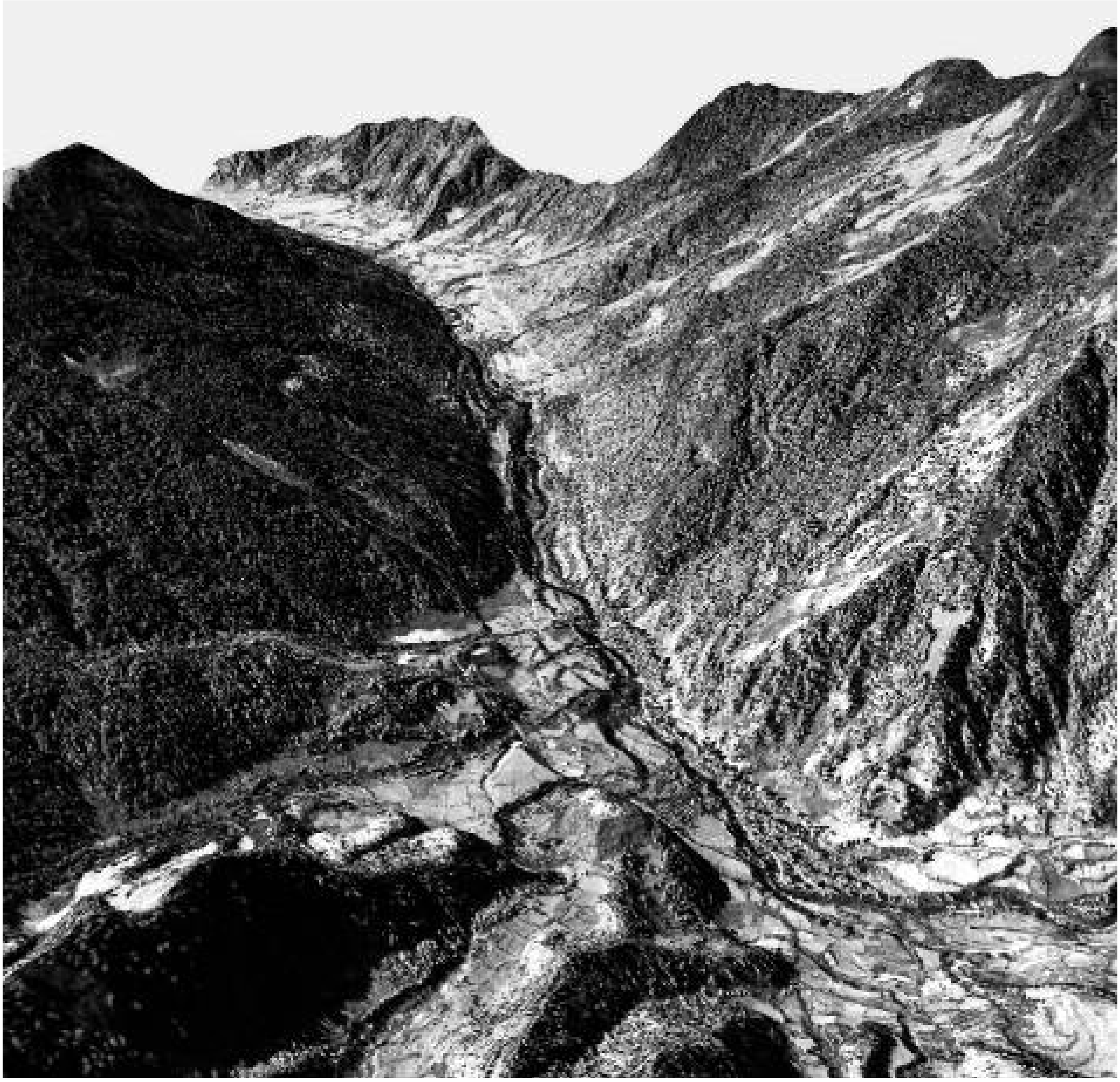

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method. For the purpose of visualization, the pan-sharpened ortho-image has been draped over the DSM in order that a textured 3D model of the landscape can be virtually viewed and navigated through (Fig. 6). Furthermore, a virtual flyover can be produced and a physical relief model can be printed in 3D if required.

Fig. 6 View towards the South on the textured 3D model generated from GeoEye-1 imagery. The Drapham Dzong hill is visible at the center of the lower part of the view.

Conclusions and Outlook

This contribution describes an intermediate stage of our work for the 3D model generation of Drapham Dzong and its environment using photogrammetric techniques. Our project is not finished yet. The current models were produced with a Bhutan exhibition at the Museum Rietberg Zurich in mind. For professional use, we still have to refine the models in some instances. We have generated textured computer models derived from high-resolution (0.50 m pixel size) satellite images, very high-resolution UAV (quadrocopter) aerial images and also from terrestrial images. In many projects, in order to work efficiently and to produce superb results, it is mandatory to use this multi-sensor approach.

Another key to success is the close-cooperation between experts in archaeology/cultural heritage and geomatics. There are many pitfalls in data acquisition and processing which can only be avoided with the help of a geomatics expert. On the other hand, when generating the models from images it is indispensable to have in-depth knowledge in archaeology, architecture, art history, etc. Otherwise the interpretation of the images by an amateur will inevitably lead to wrong results.

According to our experience, UAVs are highly suitable and effective for this kind of work. They combine high flexibility in data acquisition and fast operation at relatively low costs. It can be expected that this technology will be applied a lot more in the future, particularly pertaining to archaeology and cultural heritage applications. Operating such a device in a remote location at 3,000 m altitude is a challenge to this technology. We experienced a few problems in the field, but they were not serious enough to jeopardize our mission. It can safely be predicted that these problems will be overcome by the system manufacturers in the near future.

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