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PHOTOGRAMMETRIC RECONSTRUCTION AND 3D VISUALISATION OF BET GIORGIS, A ROCK-HEWN CHURCH IN ETHIOPIA

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ABSTRACT
Around 1200 AD, a number of remarkable rock churches were constructed in Lalibela, a town in northern Ethiopia. One construction manner stands apart in its uniqueness. This is the rock-hewn monolithic church, which while imitating a built-up structure is actually cut in one piece from the rock and separated from it by an all-around trench. The best known of the monolithic churches is Bet Giorgis (St George's Church), a UNESCO World Heritage site. The narrowness of the trench around the church makes the photogrammetric image recording demanding. Numerous photographs were necessary for a sufficient coverage. In a first phase of the 3D model generation only monoscopic image measurement was carried out. First results were not satisfactory due to problems in properly defining homologous points in the respective images. Such an ancient building suffers from erosion damages and hence lacks sharp corners and edges. Additional helpful construction features such as parallelism, perpendicularity and planarity can barely be exploited as the building is relatively irregular. For these reasons additional measurements are performed in stereo photogrammetric mode. Still, there is a high demand of visual interpretation and manual measurements are absolutely necessary for producing a comprehensive 3D model. For the 3D model rendering, the ETH-developed visualisation software *Disp3D*, which employs a view-dependent texture mapping procedure, has been used. The project, which is ongoing, will ultimately result in the production of a fine-detail visually realistic digital model of the church and its immediate surroundings.

1 THE ROCK CHURCHES OF LALIBELA

The town of Lalibela lies in the province of Wollo in northern Ethiopia, some 640 km from Addis Ababa. Lalibela is internationally renowned for its rock-hewn churches. Their creation is ascribed to King Lalibela, one of the last kings of the Zagwe dynasty. All 12 churches in the town are thought to have been constructed within a 100-year period around 1200 AD. Of the three basic types of rock-churches in Ethiopia, built-up cave churches, rock-hewn cave churches and rock-hewn monolithic churches, the last, which is of current interest, is unique to the Lalibela region. Arguably the most significant of Lalibela's four strictly monolithic rock-hewn churches is Bet Giorgis (the Church of Saint George), which is regarded as being the most elegant and refined in its architecture and stonemasonary. Fig. 1 shows the 12 x 12 x 13m Bet Giorgis standing within its 25m square trench.

Fig. 1: Bet Giorgis rock-hewn church, Lalibela.

Fig. 2: Ornaments at upper windows and weathered corners of cornices in the foreground

Legend has it that Bet Giorgis was built only after King Lalibela was reproached by Saint George (the national saint of Ethiopia) for not having built a house for him. King Lalibela's response was to build a church, the construction of which, legend tells, was supervised by Saint George in person. As is apparent from Fig. 1, the 'construction' of a monolithic rock church was in fact an excavation, the procedure being to first cut free a block of stone in the volcanic tuff, after which stonemasons chiselled out the church, shaping both the exterior and interior. The extent of the detail involved in this process can be appreciated from Fig. 2, which shows one of the upper windows of the east facade.

Bet Giorgis is positioned in its deep pit on a sloping rock terrace with the church being accessed via an entrance trench and tunnel. Around the walls of the courtyard in the pit there are caves and chambers which house both today's priests and the graves of pious former pilgrims and monks. The cruciform church rises approximately 12m from its triple-stepped supporting platform, and it has three west-facing doorways (characteristic of Ethiopian churches), nine 'blind' lower level windows and 12 upper-row windows. The interior of the church follows the cruciform floor plan and on the roof there is a relief of three equilateral Greek crosses inside each other (Fig. 1). The roots of Lalibela rock churches are thought to lie in Axumite architecture and in the early Christian basilica, yet while they may reflect a blending of eastern Mediterranean Christianity and Axumite tradition, they are also a truly unique contribution to Ethiopian Christian heritage. In recognition of their significance they have been accorded UNESCO World Heritage status (Ruther et al., 2001).

2 PHOTOGRAMMETRIC DOCUMENTATION

2.1 Project Motivation

As an aid in the long-term preservation of Bet Giorgis, and as a contribution towards making this remarkable heritage site more accessible in today's 'virtual world', a project was undertaken to photogrammetrically document the church. The project, which was initiated by Heinz Ruther, one of the authors, with support of government agencies in Addis Ababa and encouragement from UN affiliated agencies, has as its ultimate aim the creation of fine-detail visually realistic digital models of both Bet Giorgis and other Lalibela rock churches. With direct support being given to the project by the Ethiopian Mapping Authority, work commenced in October 2000 with a field trip to Lalibela (Ruther et al., 2001).

2.2 Data Acquisition

Three fundamental data sources were involved in the Bet Giorgis documentation. The first of these was existing 1:10,000 scale aerial photography covering the church surroundings. The second was ground survey data to facilitate control for the aerial imagery and to provide a tie between the local XYZ reference coordinate system used in the close-range photogrammetry and the geodetic network. The third was terrestrial imagery, to facilitate photogrammetric triangulation, geometry model generation and texture mapping for the visually realistic Bet Giorgis model.

For the close-range modelling of the church and the pit, three comprehensive sets of imagery were recorded at camera station intervals of a few metres around the top and the bottom of the pit. Three digital cameras were employed, a Kodak DCS330, a DC210 and a SONY Cybershot, as well as a Leica R5 35mm semi-metric analogue camera for possible comparative studies. For the SONY Cybershot calibration, parameters from a prior laboratory testfield calibration were employed. Both the DCS330 and the DC210 were calibrated in the field via self-calibration.

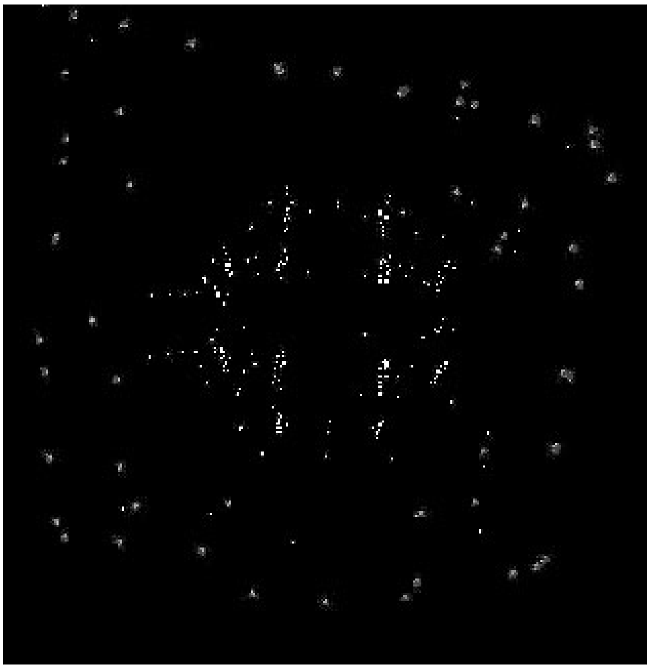

Fig. 3: 57 station, 210 point photogrammetric network. The point cloud adumbrates the cruciform church.

The 3D measurement of significant feature points on the church and pit walls was accomplished by photogrammetric means. The significant points comprised both artificial targets (see lower right of Fig. 2) attached to the rock face and natural feature points. The natural points tended to be located on features of interest for the building of a 3D model, e.g. on edges and corners of the church. Camera calibration, photogrammetric bundle adjustment and supplementary object point triangulation (with given exterior orientation) were fully carried out in the field. These needs were all met by the *Australis* software system for off-line digital close-range photogrammetry (Fraser and Edmundson, 2000). The result was a dense point cloud with known object coordinates (see Fig. 3) which could be used for subsequent exterior orientation determination (for images not in the network) and point densification through spatial intersection. Redundant, surveyed control points were employed to transform the reference coordinate system of the photogrammetric survey into the geodetic system. An analysis of checkpoint residuals indicated a *photogrammetric* triangulation accuracy of close to 1.5cm, which was consistent with expectations for an average imaging scale of 1:3000 (4.8mm lens and 15m object distance) and the 1-pixel measurement precision anticipated for the natural targets. A more detailed description of the process can be found in Ruther et al. (2001).

The photogrammetric triangulation phase was not restricted to use of the DC210. Similar networks were also processed for the DCS330 and Sony Cybershot imagery using *Australis* and *PhotoModeler* respectively, with consistent results being obtained. Several reasons justify the separate triangulation with these images, based on the points generated by the DC210 block: The resulting 3D model can be expected to become more geometrically consistent and free of problems in the overlap regions of photogrammetric models. The danger of missing or double measuring of information in the overlap regions is thus minimised, and the measurement process is more convenient.

3 3D MODEL GENERATION

3.1 Landscape Model from Aerial Imagery

From two adjacent stereo models of the aerial photography a digital terrain model with 15m post spacing along with an associated ortho-image with 0.25m ground sampling distance was generated. The aerial imagery covering approximately an area of 1.9 km square, was scanned at 25 micron resolution. The DTM and ortho-image were then generated automatically utilising the standard image correlation functions offered by LH Systems' *SOCET SET* system. Due to the mountainous terrain, the so-called "steep strategy" was employed in the image correlation, with the "snap-to-ground" strategy being used to enhance the initially generated DTM. The resulting absolute accuracy of the ortho-image is 1-2m, and the DTM is accurate to better than 1m. By combining these two products, the resulting 3D photo texture model can give an impression of the landscape surrounding the Lalibela churches, as indicated in Fig. 4.

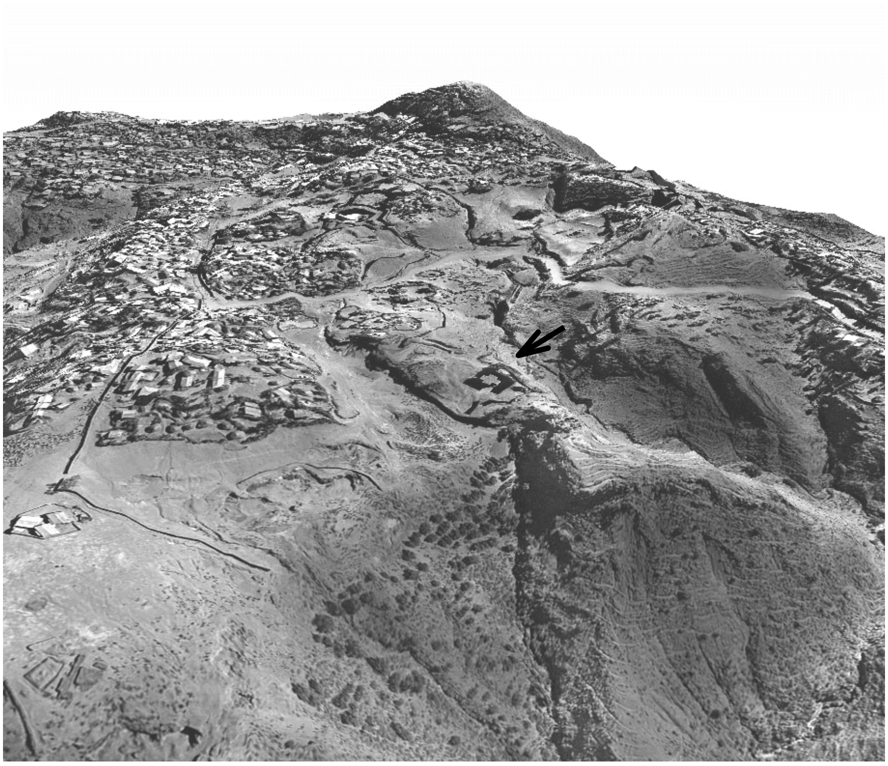

Fig. 4: 3D landscape model: Lalibela (upper left) and Bet Giorgis church (marked with arrow)

3.2 Church Model from Close-Range Imagery

The result of the photogrammetric triangulation is a cloud of feature points, some of which are useful for the 3D model generation process, and some which while not being of prime use in this regard are nevertheless crucial to the later processes of image registration, ortho-image generation and texture mapping. The next requirement, however, is generally to densify the object point array in order to include feature points needed for the geometric modelling.

This task was initially performed by only monoscopic image measurement in *PhotoModeler* (Ruther et al., 2001). Thereby the image network of the photogrammetric triangulation formed the project kernel. Particular characteristics of the building resulted in more images than expected at first sight: the inner corners of the cruciform church, the narrowness of the surrounding trench, and surprisingly intricate surface structures, for example. Therefore the new images were mainly such taken from a short distance down in the trench. 71 images finally guaranteed full overlapping coverage and favourable intersection angles, but only for the church itself. At this point it was decided to open a second project for modelling the enclosing pit. Actually *PhotoModeler* does not limit the number of project images, but a huge number makes the project handling rather complex for the user. For the pit project the network of the photogrammetric triangulation was first reduced to 28 images, the minimal number still guaranteeing a stable network around the church. New images were added stepwise till an overall number of 63 allowed a complete coverage of the walls and bottom of the pit. Again, this is a very large number of images but one has to recall that most wall images 'suffer' from occlusions in the foreground caused by the church itself. However, as most control points are located on the church itself, the images covering parts of it serve as a kind of 'support pillars' for the photogrammetric triangulation of some pure wall images in between.

It is noteworthy that in both projects every new feature point was also included in the bundle adjustment such that the strength of the network improved in a stepwise fashion with the collection of 3D model points. The number of points in the church model currently is about 1600. The work with *PhotoModeler* was not limited to point measurements alone. Regarding the 3D wireframe/texture model all connecting lines and triangle faces were also defined. Both operations had to be carried out manually.

First measurements revealed one characteristic common to such ancient stone buildings. Most formerly sharp corners and edges were rounded or even broken off due to erosion processes. As a consequence it was often impossible to properly define homologous points in the respective images. The weathered corners of cornices in the foreground of Fig. 2 and the abraded corners of door beams in Fig. 5 serve as an illustration of this characteristic. This is a minor problem for points which are visible in several optimally arranged

Fig. 5: The circles mark an exemplary indistinct corner of a door beam beside one of the artificial targets.

images. A slightly different definition in one or another image does not carry weight as the bundle adjustment process leads to an acceptable accuracy in the cm-range. But in cases where a point cannot be properly defined, and in addition is visible only on a few unfavourable images, an unacceptable error can result for this particular point. If such a point is part of a small structure, like the projecting corner beams in the doors and lower windows, the error becomes very evident in the visualisation product.

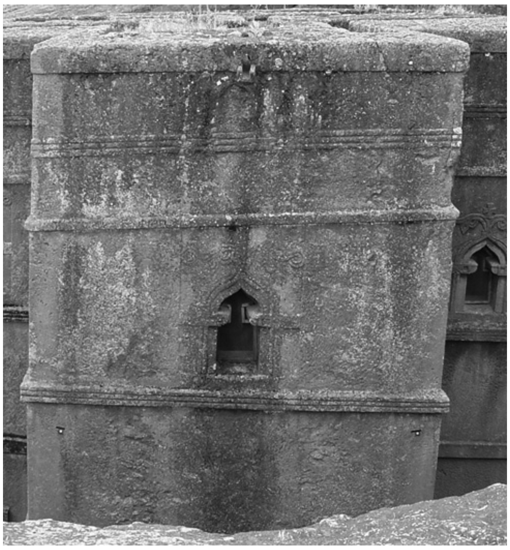

Fig. 6: Parallelism cannot be assumed.

One could think of solving this problem in a later post-editing step, e.g. in AutoCad using additional construction help like parallelism, perpendicularity or planarity. But this is problematic for two reasons. First, it can be difficult to decide which of the measured points are correct and can be used as initial construction points. Second, the building is relatively irregular due to its unique method of construction. Even primary surfaces contain many irregularities in geometry, such that straight edges of substantial length and planar surfaces of significant size are not in abundance. Fig. 6 illustrates that parallelism conditions in some places are not useful. At this point it shall be mentioned that CAD-reconstruction is nevertheless necessary for hidden points where no image information is available. This underlines the importance of high accuracy and reliability for any measured points.

The solution to this problem is measurement in stereo mode. Already at image recording this particular evaluation mode was taken into account by recording numerous image pairs. Specially written software, supported by OpenGL and SGI, is currently used for the stereo measurements. With stereo view an operator can measure a damaged corner at its correct place taking into account the geometry of an object. What of course remains is the generalisation question. How shall a damaged corner beam be modelled? In its original geometric form including a limited number of points, or with its broken corners, which increases the number of points significantly? One has to take into account that at this point there is no room for automation. In general the purpose of a 3D model defines the demands regarding the level of detail. For this project no clear guidelines exist. At the current state irregularities are included if they are connected to the unique method of construction, and erosion-damaged areas are only visualised with photo texture. In spite of this restriction, a comprehensive CAD model over the whole church area has been constructed, but will be updated in the near future.

4 TEXTURE MAPPING AND VISUALISATION

With the technique of texture mapping, grey-scale or true color imagery is mapped onto the 3D geometric surface in order to achieve photorealistic virtual models, as indicated in Figs 7 and 8. Knowing the parameters of interior and exterior orientation, the corresponding image coordinates are calculated for each triangular face of the 3D surface. The grey-scale or color RGB values within the projected triangle are then attached to the face. Two approaches were adopted for this task, one at UCT, Cape Town and the other at ETH, Zurich.

The former essentially comprised the following steps: exterior orientation determination, image rectification/ortho-rectification and texture mapping. All these tasks were performed with *PhotoModeler*. The latter employed an ETH-developed visualisation software called *Disp3D*, which is described in detail in Grün et al. (2001). In the current project *Disp3D* imports triangular object faces defined in *Photomodeler*. For each face a combination of image content is calculated from all images where a particular triangle appears. The procedure consists of three steps: pre-processing, selection of a geometrically optimal image and texture weighted averaging.

(1) Pre-processing: In order to achieve a bigger local contrast and nearly the same color balance in all images, highpass filtering and histogram equalization are used for each RGB channel separately. In the case of the Bet Giorgis model the two separate *PhotoModeler* projects, for the church and the pit, were processed separately in *Disp3D*. For the church images no filtering was necessary as they already were well balanced. Wallis filtering was applied with a patch window of 150x150 pixels for the pit images. Still there remained some checkerboard effects on the walls of the pit.
(2) Selection of a geometrically optimal image: In all image planes where a particular triangle is projected, the area of the triangle is calculated. The image where the triangle appears largest contains the most texture information. If dealing with a complete model an eventual occlusion of relevant texture information by objects in the foreground of the image is automatically taken into account. As the Bet Giorgis model was separated in a first phase, some manual editing was necessary at this point.
(3) Texture weighted averaging: All remaining images are considered where a particular triangle appears simultaneously. The values of these images are averaged according to a weighted average procedure in order to reduce the effects of radiometric differences in adjacent images.

If an object face is not visible on any image it cannot be mapped. In the case of the Bet Giorgis model this happened only for minor faces at the inner corners of the cruciform building. Here texture from similar, better visible elements was taken. Very oblique images also cause problems, as the texture information for a particular face is strongly smeared when rectified. Here mainly the top of the church is affected as no suitable high image viewpoints were available.

Fig. 7: 3D texture model generated with *Disp3D*.

Another disturbing effect arises from the subdivision of the model into triangular faces. Depending on the illumination of the 3D model, the single faces become visible even when having only small differences in inclination. The solution of dissecting nearly planar faces in as few triangles possible would help but fails in the case of adjacent detailed structures. In addition, irregularities in the planar faces would eventually be lost. Another solution would be a segmentation into even more small and approximately equilateral triangles, which would model all discontinuities properly and at the same time reduce the disturbing effects caused by illumination of the 3D model. Without automation this process would be an immense task. *Disp3D* already includes basic automation functionality such as image matching tools; indeed these still have to be adapted for the task of building modelling.

Disp3D delivers the following visualisation functions: point cloud; wireframe with hidden lines; shaded surface; and texture map in mono and stereo display, via anaglyph projection and polarized stereo. Image streams for MPEG-1/MPEG-2 videos can also be created. The final textured model can be viewed with *Disp3D* or it can be converted to VRML2 for viewing with standard visualization packages. Our model will also be made available on the Web at a later date.

Fig. 8: Portion of 3D texture model (available in colour).

5 CONCLUSIONS

Ruther et al. (2001) refer to a changing paradigm in the photogrammetric recording and documentation of cultural heritage sites, a topic also discussed in Patias & Peipe (2000). Recent enhancements of the photogrammetric approaches are highlighted and among these is a trend away from stereo models to multi-image surface reconstruction. During the photogrammetric reconstruction of Bet Giorgis church it became obvious that stereo measurements still are of considerable importance in building a high quality model to fine detail and resolution. Our experience does not challenge the fact that in most situations multi-image techniques in mono mode are more appropriate. Instead, it simply illustrates that stereo still has much to offer as a complementary technique, especially in cases where a good framework of ‘control’ has been build via the monoscopic photogrammetric process and where 3D visual interpretation is necessary for feature definition.

Digital still video cameras have proven to be a very appropriate device for such kind of work. Fast image recording and storage, sufficient accuracy performance, together with the ease of use makes them an excellent choice, especially for this exploration-type of project. However, if high quality texture mapping is required one should pay much more attention to illumination conditions and to the geometric relations between image planes and major object faces. This is a significant change in recording concepts, compared to the traditional approach, which was based on wireframe model optimisation and minimisation of the number of images. Denser image sequences will solve some of these problems and also simplify any automated or semi-automated processing tasks.
The conduct of the Bet Giorgis documentation is otherwise very much in accordance with the new paradigm referred to above, and it is the hope of the authors that once the visually realistic digital modelling of this church and others in Lalibela are complete, a valuable information source will have been generated for use in site conservation, historical and architectural studies, education related to Ethiopia’s rich heritage and history, and in visualisation for general enquiry and tourism.

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