PHOTOGRAMMETRIC RECONSTRUCTION OF THE
MY SON "G1" TEMPLE IN VIETNAM

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ABSTRACT:

Mỹ Sơn Sanctuary comprehends several ancient Hindu temples and is the most foremost heritage site of this nature in Vietnam. Part of the complex is today seriously damaged and needs restoration works. The temple G1 addressed in this work represents a pilot case to establish a workflow for both documentation and conservation purposes. Both aims required as primary need the 3-D digital reconstruction of the object. The current conditions of the temple and the presence of inhomogeneous textures on its walls made the reconstruction process quite complex. Due to the impossibility of using a terrestrial laser scanning for economic and environmental problems, a low-cost photogrammetric solution was adopted to carry out data acquisition, image orientation and 3-D reconstruction of the temple. The small cost of the camera (a Nikon D80) and the user-friendliness of the SW PhotoModeler 6 Scanner allowed also people not fully skilled in photogrammetry to give an important contribution to this project. In addition, an algorithm for automatic orientation of marker-less image sequences through a Structure and Motion strategy was used to check its applicability for further surveys, in order to speed up and to make automatic the process. The paper will also shows different types of final products that can be yielded and delivered (3-D vector model, orthophotos, anagliphic images for 3-D stereo visualization).

1. INTRODUCTION

1.1 The historical site of Mỹ Sơn

The monumental area of Mỹ Sơn, extends over almost 15 ha in the Quảng Nam province (central Vietnam), approximately 30 km South-West from the city of Đà Nẵng. The area is located in a small valley surrounded by a semicircular chain of low mountains, upon which rises mount Hòn Châu, also named *Răng Mèo* ("the cat's tooth") by the local population for its peculiar shape (Fig. 1).
Between the 7th and 12th century, the Cham people, of Hindu religion, built more than seventy brick masonry buildings in this area, thirty of which are still recognizable.
The principal temple (*kalan*) was an isolated building only in rare cases, since a religious complex usually consisted of a sanctuary with several annexes. Almost eleven religious Hindu complexes (usually referred to as "groups") are still recognizable in the Mỹ Sơn area (Fig. 2).

Figure 1. Mỹ Sơn: view of groups C and D with the Răng Mèo in the background.

The discovery of the site dates back to 1885 by a squad of French soldiers. In 1901 a research in the architectural and historical-artistic field started, thanks to the work of Henri Parmentier, chief architect of the EFEO (Ecole Francaise de l'Extreme Orient): he classified every group with a letter (from A to N) and every building with a number, with the aim of making the study of the buildings easier (Parmentier, 1909-1918).
During the war against US, in 1969, the buildings which had survived were severely bombed, with astonishing precision, and many were razed to the ground.
The authors work was developed in the framework of a preservation project on group G, which involves Politecnico di Milano, the Institute for Conservation of Monuments of Hanoi and UNESCO.
The choice of group G (Fig. 3) was determined by important factors for the purpose of archeological research: among the monumental groups of Mỹ Sơn, it shows peculiar and homogeneous characteristics, as for the architecture as well as for the decorations. Moreover, since it was built in the period of decadence of the Cham civilization (following the opinion of French scholars – Parmentier, 1948), it was never restored. An important characteristic of group G, in common with the other monumental groups of Mỹ Sơn, is the peculiar structure of the masonry, with bricks of different shape connected by very thin joints of organic material.
Group G consists of five buildings (*kalan, maṇḍapa, gopura, pośa, kośagrha*) situated on a low conglomerate hill and built between the XI and XII century. For their type and function, they represent a unitary and well defined example of religious Hindu architecture. The main temple (G1), which contained the divinity, is in the centre of the sacred area; the other buildings are annexes, mainly used to preserve the sacred texts and objects used during the religious rituals, as well as the founding memorial stone, and to gather the pilgrims. A geometrical survey was carried out to allow the exact determination of the position and geometry of the group G buildings, providing both metric and qualitative information. The survey allowed the shape of the hill, as well as the orientation of the buildings to be properly defined: the Group is oriented mainly along

the East-West axis, with the entrance at the East side (Fig. 3).

The main temple (14.5 m long and 9.0 m wide) is characterized by the presence of four fundamental elements: the foundations, the base, the central body and the roof (Fig. 4).

The most important part of the temple is the cell (*garbhagrha*), where the divinity was guarded. The dimensions of the cell are 3.10×3.20 m; there are small niches, carved in the masonry, where the lamps were placed, since the cell has no windows. The surveys carried out in combination with the excavated foundation pits by the archeologists allowed the determination that the foundation depth is limited to a reduced portion of soil, with a thickness close to that of the masonry; there are no footing.
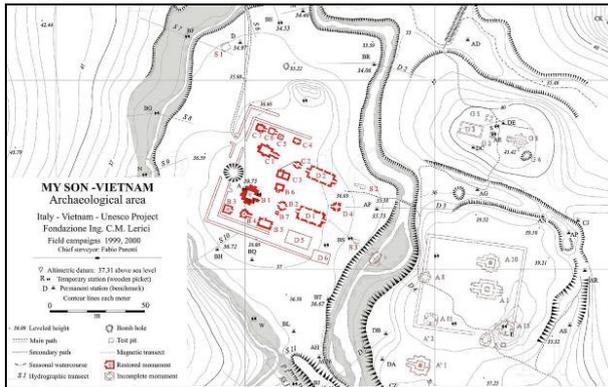

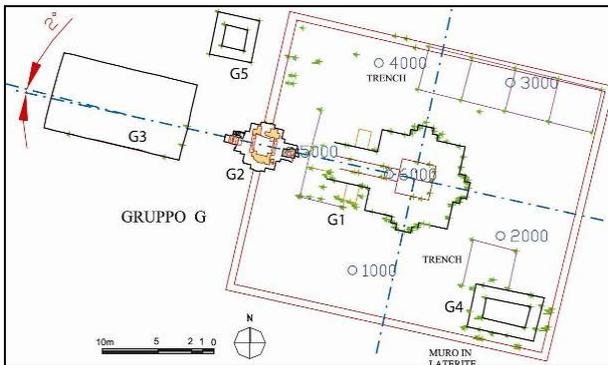*Figure 2. The archaeological area of Mỹ Sơn.*

Figure 3. Orientation of the buildings belonging to Group G.

Nowadays the building is in the state of ruin, with a maximum elevation of only 6 m. Around 1900, during the research carried out by Parmentier, it was already in bad condition. At that time, almost no remains of the roofs of group G were left, with the exception of a small part in G1. The stability of several parts was endangered: the lintel of the main entrance was already broken, and one of its part had rotated and thus detached from the masonry (Parmentier, 1948). The most relevant damage occurred during the Vietnam war. The whole part of the northern entrance and the only remaining connection between the cell and the vestibule collapsed, as well as a small part of the eastern side of the cell. Moreover, the bombings severely jeopardized the overall stability of the structure.

The state of damage increased during the years because of the lack of a regular maintenance, which is the main cause of the vegetation growth: several roots penetrated the masonry, worsening the crack pattern .The overall structural stability is mainly endangered by the lack of the roofs and by several cracks, passing through the entire wall thickness.

In order to prepare a design for the intervention, based on the principles of conservation (Binda *et al.*, 2006), a careful geometrical survey was necessary, taking into account that most of the upper part of the building is constituted by ruins deposited after the failure of the roof. These parts have to be carefully removed, piece after piece and rebuilt possibly using the recovered original bricks. So it is important to document the position of all these parts and their shape in order to restore them. Furthermore, only by detecting the position of the main cracks it will be possible to decide how to carry out the intervention in different steps, in order to avoid partial or total collapses. Being the shapes highly irregular it was not possible to carry out the geometrical survey by usual topographic tools as total stations. The use of a *terrestrial laser scanner* was a too much costly for the existing budget given by UNESCO, so only a low-cost photogrammetric approach was viable.

Furthermore the detailed survey will allow to implement a mathematical model studying the behaviour of the building before and after the intervention in order to check its safety level.

Figure 4. General view of the South-West side of G1.

1.2 General description of the photogrammetric project

The project was organized in three main steps, to be accomplished by different working teams in a coordinated research group.

First of all, object signalization, total station measurements and image acquisition were carried out during the month of July 2008. People not already experienced in photogrammetric performed this stage on-site. A preliminary design of the block was carried out in Italy with the support of photogrammestists. Details about this stage are reported in Section 2.

Secondly, camera calibration and orientation with a semi-automatic procedure (see Sub-sec. 3.1) were carried out in Italy by the SITE group (Surveying Information Technology for Environmental and cultural heritage) at BEST Dept. of Politecnico di Milano. However, images for calibration were captured on site before each data acquisition session.

Finally, the 3-D reconstruction and editing of the vector model of the temple has been completed by people experts in masonry structure restoration and conservation (Sub-sec. 4.1) at DIS Dept. of Politecnico di Milano.

At the same time, the group SITE dealt with testing on the same datasets an alternative orientation procedure based on a Structure and Motion approach; this task is described in Sub-section 3.2 and compared to the standard technique (Sub-sec. 3.3). Similarly, the automatic reconstruction of the surfaces of the temple was carried out by using image matching techniques.

Different products have been obtained from this project (see Sec. 5), whose main aim was to derive data to apply structural analysis (*Finite Element Modeling*) and to draw conservation works. According to the complex and irregular structure of the considered buildings, the traditional products of a photogrammetric or total station survey are not adequate to give a support for the conservation project. On the other hand, here 3-D products and photo-realistic visualization tools play a fundamental role for both F.E.M. analysis and for data interpretation and understanding.

2. DATA ACQUISITION

The survey of the temple was carried out with a photogrammetric approach integrated with total station (TS) measurements.

The images were captured with a Nikon D100 camera (3008×2000 px) and a Nikon D80 camera (3872×2592 px) with two different lenses: a 18 and 24 mm, respectively. These lenses were interchanged with the used cameras. Camera calibration was performed just before the image acquisition of the temple by using the self-calibration procedure implemented into software PhotoModeler (Eos Systems, 2009).

All images were acquired under a circular block around the temple, in order to capture a sequence of several ordered images which results useful for both standard photogrammetric orientation (Sub-sec. 3.1) and for an alternative procedure based on Structure and Motion (Sub-sec. 3.2).

Furthermore, several coded targets were applied on the façades of the temple to help semi-automatic image orientation. A complete automatic reconstruction with coded targets was not possible for problems during the automatic identification of some targets. These targets were also measured with a TS, but the measurements on the four façades were not connected among them through a geodetic network or a traverse, then they resulted independent. Topographic measurements will result useful to check the accuracy of the photogrammetric results.

The images were taken in two days and several dataset were acquired at different hours (in the early hours of the morning, midday and the evening) to compensate for some drawbacks. Indeed, the warm climate influenced the image quality for the air refraction. All images were acquired with a photographic tripod. Globally 12 image datasets were acquired and 2 were selected as the best ones for further processing.

3. IMAGE ORIENTATION

Image orientation was carried by using two different datasets. The first dataset is made up of 26 images acquired with a Nikon D100 camera with a 24 mm lens, while the second one is composed of 27 images acquired with a Nikon D80 camera with a 18 mm lens. Other datasets were available (same cameras with different lenses) but these two datasets were identified as the best ones after a visual check.

Both selected datasets are shaped in circular blocks around the temple as described before.

3.1 Semi-automatic orientation with coded targets

On the façades of the temple many coded targets were applied in order to improve the automation of the orientation procedures. These targets were measured with a *Least Squares matching* algorithm (Gruen, 1975) and homologous points were automatically identified by using an opportune coding. In any case, during this phase some errors were found and a manual correction was necessary before processing the entire block. These errors were generally due to a partial occlusions of the imaged targets.

The orientation of both sequences was performed by including self-calibration.

At the end of the relative orientation step, the model was scaled by using several interdistances between the targets on the different facades. No absolute orientation of the model was carried out, because TS measurements were not connected between them and the measurements on the facades were independent.

The quality of the two projects was estimated by using a check based on the interdistances between targets. In fact, a distance is independent from the considered reference system and appears as a good solution in this step. The distances of both photogrammetric models were compared with the Total Station measurements which were assumed as reference These results are shown in Table 5. As it is possible to see, Nikon D80 dataset appears better but in both cases the maximum error is always lower than 20 mm.

Camera poses for block captured with Nikon D80 camera are shown in Figure 6, where it is possible also to see the interdistances between targets used to fix the scale of the photogrammetric model. After this considerations, Nikon D80 dataset is chosen as a reference for next processing steps.

Facade	North	South	East	West
Nikon D80				
mean (mm)	0	0	-3	2
std.dev (mm)	4	3	4	4
max (mm)	11	6	14	11
min (mm)	-15	-9	-8	-7
Nikon D100				
mean (mm)	-1	-2	-3	2
std.dev (mm)	5	4	7	5
max (mm)	10	5	20	16
min (mm)	-19	-16	-15	-10

Table 5. Comparison between targets interdistances evaluated from TS measurements and with standard photogrammetric orientation (Sub-sec. 3.1).
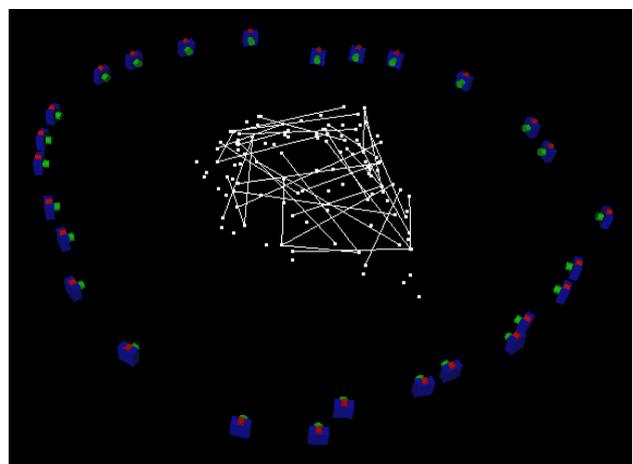

Figure 6. Camera poses and distances used to fix the scale on the photogrammetric model.

3.2 Automatic marker-less orientation through Structure and Motion

The orientation of the temple images was also performed with an algorithm which allows the automatic relative orientation of sequences. This algorithm (Barazzetti & Scaioni, 2009) can automatically orient a sequence of ordered images if they present a good overlap (larger than 80%). In particular, each image must present an overlap with the next two images. The algorithm can also be used to process an image block with generic shape as shown in Scaioni *et. al* (2009), i.e. also if it is not structured as a sequence. This version was not applied to this project. Input elements are calibration parameters and the image sequence.

The algorithm executes a preliminary *feature-based matching* between triplets with SIFT (Lowe, 2004). Then an outlier removal based on pairwise robust estimation of the *fundamental matrix* is carried out in order to remove any possible error during the identification of the homologous points with the *Lowe descriptor*. Furthermore, the algorithm can improve the estimation of the image coordinates of tie points by using *area-based matching* techniques like *normalized cross-correlation* and *L.S. matching* (LSM). In this case, to check the accuracy of an orientation based on the feature matching only, original images were compressed to a resolution of 1500×1004 pixels and no LSM refining was used.

The orientation procedure is based on a progressive resection alternated to intersection in order to concatenate all images to a reconstruction obtained from a triplet assumed as reference (images 1,2,3 in this case). The procedure is similar to a *Structure and Motion* (S&M) approach, which is familiar in Computer Vision community, but is based on collinearity equations. This means that inner orientation parameters must be known for each image.

The particular geometry of this sequence (like a closed ring) allows a matching between the first image with the last one, in order to close the sequence and reinforce the geometry of the project.

Only images acquired with the Nikon D80 camera were used, but the original dataset (27 images) was expanded to 41 images to ensure a better overlap. The scale of the model was fixed by using only a distance on the South façade,

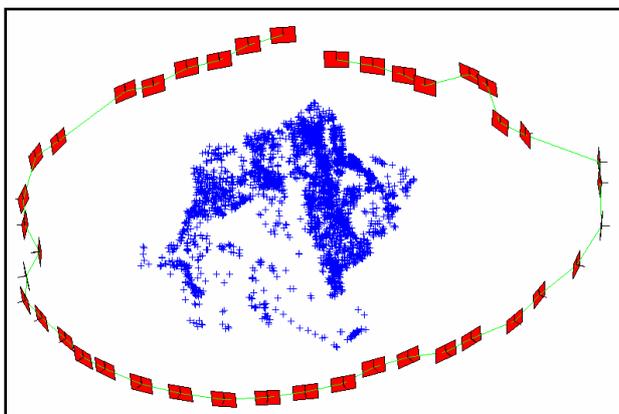Camera poses after the orientation with this algorithm are shown in Figure 7.

Figure 7. Camera poses of the oriented block around the temple.

3.3 Comparison between different approaches

To perform a comparison between the model created with the semi-automatic procedure with targets and the model with the S&M algorithm, an analysis based on target coordinates was carried out. For this check, after the orientation of the images with the automatic algorithm all targets were measured and their object coordinates computed. In any case, no bundle adjustment were applied after the manual measurement of this new points.

A first analysis based on the interdistances between targets was performed. In this case, photogrammetric measurements were compared with the TS ones. In Table 8 the results with the S&M algorithm are shown (while results with the semi-automatic approach are shown in Table 5).

Façade	North	South	East	West
mean (mm)	5	0	10	14
std.dev (mm)	3	5	7	8
max (mm)	13	14	27	34
min (mm)	-1	-26	-4	-17

Table 8. Check on the interdistances on the model created with the S&M algorithm.

As it is possible to see, façades North, East and West present a systematic error. This is probably due to the scale factor fixed only on the South façade (which is bias-free).

A second check was performed by using 3-D coordinates. This analysis was based on computing a roto-translation with isotropic variation of the scale of the photogrammetric model coordinates, in order to compare them with the TS measurements. The four façades of the temple were analyzed independently, because topographic measurements are not all referred into the same reference system. Results of this analysis are shown in Table 9.

The variation in scale of the transformation allows the systematic errors removal. The results with the two methods appear quite similar. In any case, the automatic reconstruction with the automatic method was performed by using only a feature matching approach and so without using full resolution images. From this point of view, the use of LSM probably will allow an improvement of the results.

4. 3-D OBJECT RECONSTRUCTION AND MODELLING

4.1 Vector model from manual mono-plotting

Within the ambit of the conservation project of G1, the generation of a three-dimensional model of the structure was mainly aimed at allowing for an effective evaluation of the most critical structural alterations and weaknesses being suffered by the monument. This knowledge is necessary for a proper calibration of the temporal planning of the intervention measures.

Therefore focus was made on the description of the geometrical alterations and irregularities presumably related to structural problems whilst decorative surfaces were neglected due to the unfavourable combination of the high time-consumption and poor effectivity of their reproduction.

The model was generated by resorting to photogrammetric description of the geometry.

Semi-automatic orientation (with targets)											
Façade	North			South			East			West		
	x	y	z	x	y	z	x	y	z	x	y	z
mean (mm)	0	0	0	0	0	0	0	0	0	0	0	0
std.dev (mm)	2	3	3	2	3	1	1	3	2	2	3	2
max (mm)	4	5	4	2	4	2	2	7	4	4	5	3
min (mm)	-3	-6	-12	-4	-7	-2	-3	-7	-7	-3	-6	-3

Automatic S&M orientation (marker-less)											
Façade	North			South			East			West		
	x	y	z	x	y	z	x	y	z	x	y	z
mean (mm)	0	0	0	0	0	0	0	0	0	0	0	0
std.dev (mm)	2	3	1	6	5	4	4	6	3	2	6	2
max (mm)	2	5	2	15	14	5	6	10	8	3	8	3
min (mm)	-4	-6	-2	-12	-6	-8	-7	-8	-3	-4	-13	-2

Table 9. Comparison between photogrammetric coordinates obtained with different procedures and TS ones, after roto-translation and variation in scale to compensate for a scale error.

To this aim, the positions of 5244 material points identified by means of 27 photographs taken along radial directions (Nikon D80 dataset) were acquired, the average number of points per image amounting to 447.

The images had been taken under two different light conditions corresponding to as many times of day, which helped their interpretation. Only the pictures taken at midday time were used for data elaboration while the afternoon ones were adopted as a comparison tool.

Critical points were identified on a large number of pictures (even more than 5) and in some cases visual inspection was necessary to corroborate the interpretation of the images.

The development of said manual model took approximately 45 man-day workload.

In Figures 10 and 11 the whole 3-D model and a detail of the vestibule are reported.

4.2 DSM creation with PhotoModeler Scanner

The version "Scanner" of PhotoModeler 6 allows the point clouds generation from images. Once images are oriented, a *dense matching* process can be carried out to extract a point cloud (with sub-pixel accuracy) from the images. The matching procedure is based on image pairs only. This represents a limit because generally a point can be matched in many images and information which come from external orientation parameters are not used. In this sense, a matching between image pairs only can be considered as a first approximation.
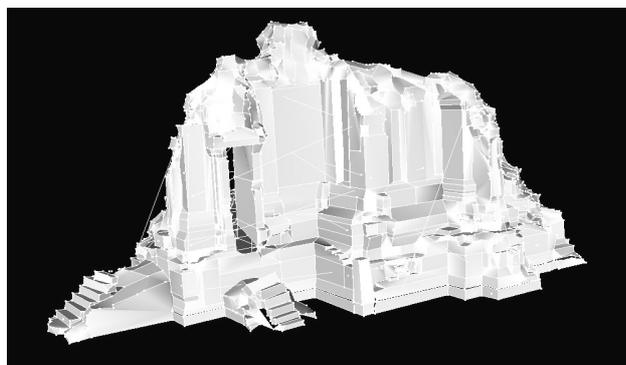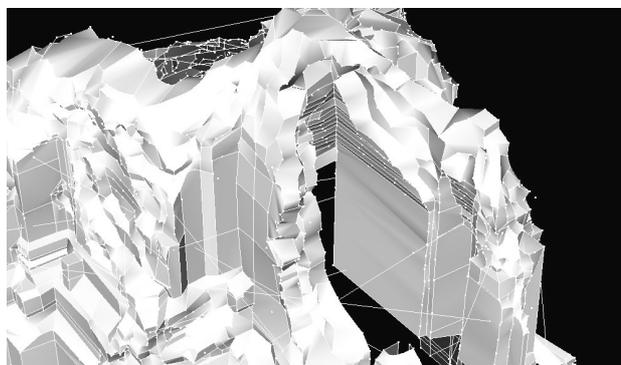

Figure 10. South-west side view.

Figure 11. View of the vestibule.

In any case, PhotoModeler Scanner is the first low-cost software which allows a point cloud creation. Many other photogrammetric software (Remondino & Menna, 2008) have tools for DSM generation but their price is not comparable with the price of this package.

PhotoModeler Scanner was used to extract point clouds with both image datasets: semi-automatic (target based) orientation and fully automated (marker-less) with the implemented S&M technique.

In the first case, the tool "Scanner" was directly utilizable because also the entire orientation process was performed with the basic version of PhotoModeler 6. In the second case external images and orientation parameters were imported into the same software.

From the two datasets two point clouds were extracted (16M and 14M points respectively, see figure 12 for some examples) by matching consecutive images. This matching procedure was really slow and almost two months of work were necessary. The used computer is an Intel Core 2 CPU 2.13 GHz, with 2 GB RAM. In addition many blunders must be manually removed. At the end of the process some gaps were found. Finally, the creation of a mesh with the tool of this software was impossible and even the data visualization became really slow. Probably this software is not designed to deal with a so large number of images.

In any case, although very slow, PhotoModeler Scanner allowed one to create two point clouds from both datasets. They are sufficient for the 3-D reconstruction of some elements which

compose the temple, but the creation of a complete 3-D model was impossible because of many occlusions (scaffoldings, boards,…). Moreover, horizontal elements could not be reconstructed from images. Other problems were founded close to vegetation and highly damaged parts. Planar elements are correctly reconstructed. Point spacing resulted in the range 3-4 mm roughly.

In addition a global DSM was created for orthophoto generation.

Figure 12. The top image reports the whole point-cloud reconstructed from original resolution images. The middle and bottom images depict some details of the 3-D model.

5. FINAL PRODUCTS AND DELIVERABLES

5.1 3-D CAD vector model

Once the geometry of the structure had been reconstructed from photogrammetry, the 3-D model was imported into a CAD environment (Autodesk AutoCAD®) for further elaboration.

In this context, some details such as those related to the staircases, whose consideration would not have been possible or precise in the photogrammetric survey, were edited. In particular, only the reproduction of the steps was possible for the North staircase because supporting sacks were obstructing the view in all pictures. The geometry of the remaining parts of the staircase (parapets and main body) was therefore acquired by resorting to the data available from the manual survey. The obtained model (figure 13) is suitable for import in structural analysis F.E.M. codes.
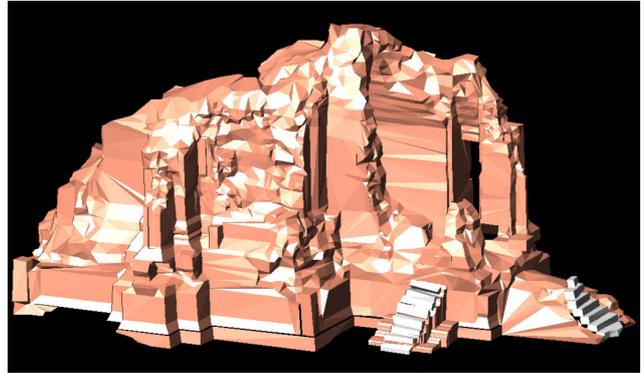

Figure 13. North side view of the temple G1; the North staircase added during editing in AutoCAD® is visible.

5.2 Photorealistic 3-D model

A complete 3-D model from the extracted point clouds could not be created. In fact, both point clouds present several gaps due to occlusions (scaffoldings, boards, etc.). In any case, during this phase it is not necessary to build a complete photorealistic model but a simple 3-D model is more than sufficient for stability analysis.

Some examples of the 3-D reconstruction of some parts of the temple are shown in Figure 14. As it is possible to see, horizontal parts cannot be reconstructed.

Figure 14. After the mesh creation many gaps remain.

5.3 Orthoimages

The point clouds extracted with PhotoModeler Scanner were used to generate a DSM for the creation of orthophotos. Point clouds were registered with an ICP algorithm (Besl & McKay, 1992).

The procedure was performed with the photogrammetric digital station Z-Map Photo by Menci Software (Arezzo, Italy – Menci, 2009), which allows the DSM creation and the orthorectification process. This package can support aerial and close-range images.

The complex geometry of the object and the occlusions made the orthorectification process difficult. For this reason several orthophotos imaging different parts were created in order to compensate for all these problems. In Figure 15 an orthoimage is shown, where 1 pixel is 3 mm.

Figure 15. A piece of orthophoto of a detail of the temple G1 wall (1 pix = 3 mm).

5.4 Anaglyph images

Anaglyph images are used to provide a stereoscopic 3-D effect, when viewed with 2 coloured *anaglyph glasses* (each lens has a chromatically opposite colour, usually red and cyan). Images are made up of two colour layers, superimposed, but offset with respect to each other to produce a depth effect. The picture contains two differently filtered coloured images, one for each eye.

Several close-range photogrammetric software allow the generation of anaglyph images, which are a useful tool for documentation and visualization purpose. In Figure 16 two different anaglyph views of the temple G1 are reported.

6. CONCLUSIONS

The paper describes an application of low-cost photogrammetric techniques for the surveying and 3-D reconstruction of the temple G1 in Mỹ Sơn (Central Vietnam). This experience has represented a pilot case study to possibly extended the same method to survey other historical buildings on the same settlement. The aim of the project is 3-D reconstruction for documentation and for the design of future conservation works
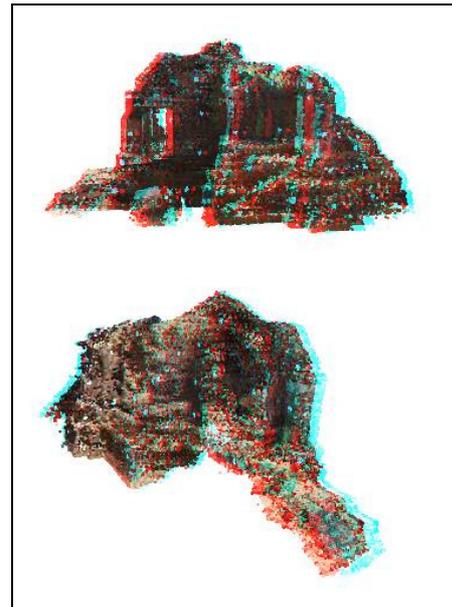

Figure 16. Two anaglyph images of temple G1 generated from different point of view.

The results of the tests have been considered fully satisfying by researchers dealing with the conservation of the temple. Indeed, the geometrical survey carried out on-site allowed to have a 3-D reconstruction of the details of the building with an appropriate resolution. The 3-D model obtained and all the 2-D sections will be used to define the design project for the intervention in all the possible phases, so that all the steps and the details for the restoration can be clearly stated before the real intervention will be started. Furthermore being the knowledge of the geometry and of the crack pattern and damages so deep, it will also be possible to state even after the site will be open necessary modifications to the project, due to finding of unexplored parts inside the walls.

In addition, the adopted approach can be considered economically sustainable, operationally viable and not requiring too high expertise in photogrammetry. Exception is represented for the data acquisition design and for setting up projects in commercial software, where the contribute of photogrammetrists is relevant.

Unfortunately, the time required to carry out all photogrammetric tasks is still to high and many efforts in the automation of procedures are needed. If camera calibration and image orientation have reached a good level of automation also in commercial photogrammetric packages, they require object signalization with coded targets to work in a proper and reliable manner. Here a procedure for automatic exterior orientation based on a Structure and Motion approach was successfully applied. This requires the image block is captured as a sequence, but an extension of this method has been proved to correctly run on general shape block as well.

A second aspect to be developed to make less time-consuming the 3-D reconstruction process is the automatic surface generation through *dense-matching* algorithms. Here a solution implemented into a well-known commercial photogrammetric software (PhotoModeler Scanner, Eos Systems) was adopted. However, algorithms in here are less evolved as the state-of-the-art of *image matching* is (Remondino & Menna, 2008). Future research and developments will be focused on improving this stage.

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