3D survey and virtual reconstruction of archeological sites

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1. Introduction

In the last decade the use of 3D acquisition techniques in the archeological field has allowed to widen the scope of the geometric survey process, providing high resolution *reality-based digital models* capable to be linked with different historical documentations, greatly improving the conventional bi-dimensional hand-made survey with a consequent gain of knowledge for the archeologists.

Another possible output, supported both by reality-based models and historical data, can lead to the generation of suggestive 3*D digital reconstructions* of architectures not anymore existing, made lively through Computer Graphics. These can be useful for a careful interpretation of the existing ruins but sometimes they might also be capable to suggest new archeological discoveries.

A weak part of the latter process is represented by the possible lack of scientific reliability on the reconstructed model, due to the actual disjunction between the modelers producing the final computer graphics output, and the archeologist owning the knowledge for creating the appropriate reconstructive hypotheses. The methodology here proposed is based on a first extensive 3D documentation of the site in its current state, followed by an iterative interaction between archeologists and digital modelers, leading to a progressive refinement of the reconstructive hypotheses. The starting point of the method is the reality based model, that, together with ancient drawings and documents, is used for generating the first reconstructive step.

Such rough approximation of a possible architectural structure can be annotated through archeological considerations that have to be confronted with geometrical constraints, producing a reduction of the reconstructive hypotheses to a limited set, each one to be archeologically evaluated. This refinement loop on the reconstructive choices is iterated until the result becomes convincing by both points of view, integrating all the available starting data in the best way.

The aforementioned approach to the digital reconstruction problem has been verified on the ruins of five temples in the Mỹ Sơn site, a wide archeological area located in central Vietnam. Created by the ancient Cham civilization active in Vietnam from 7th to 18th century, it has been listed as UNESCO World Heritage in 1999. Mỹ Sơn area contains a reasonably well preserved system of 78 Cham Temples, some of them destroyed by the nature in the last centuries (Ky Phuong et al., 1990). The integration of 3D surveyed data and historical documentation has allowed supporting a digital reconstruction of not existing architectures, developing their three-dimensional digital models step by step, from rough shapes to highly sophisticated virtual prototypes. The 3D acquisition and modeling of a specific set of five temples, indicated by the archeologists as "G group", is presented here and methodologically discussed.

2. Methodology

Although the process supporting the transformation from a set of 3D point clouds to a polygonal model is well known since more

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Table 1
3D laser scanner configurations.

Scan scale	Operating distance (m)	Resolution	
		Qualitative	Quantitative (mm)
Framework	8–16	Coarse	7–60
Architecture	4–8	Medium	4–15
Details	1	High	2

Table 2
Number of point clouds acquired at different resolution levels (first three columns), and total number of 3D points acquired (last column).

	Resolution			Size (points × 10^6)
	Coarse	Medium	High	
G1 (Kalan)	7	43	22	126
G2 (portal)	/	9	/	21
G3 (assembly hall)	/	8	/	15
G4 (south building)	/	13	/	31
G5 (pavilion for the foundation stone)	/	6	4	4
DTM	49	/	/	27
21 Finds	/	/	60	2
Total	**56**	**79**	**86**	**226**

than a decade (Levoy et al., 2000; Bernardini and Rushmeier, 2002; Beraldin et al., 2002), it has been progressively improving to better suit the Cultural Heritage field (Guidi et al., 2010). For this reason many advances have been suggested in the last years in order to optimize this process for the archaeological field (El-Hakim et al., 2008; Guidi et al., 2009; Remondino, 2011).

The reality-based digital model, generated through laser scanning of the ruins, had a double purpose in this project. On the one hand it allowed an accurate documentation of the current site status, a valuable source of information for interpreting Cham architectural structures and the possibility to analyze it with a great level of detail on a PC, possibly far from the site or in a different time. On the other hand it was a starting point for a digital reconstruction of the group G structure as it was at its foundation, that can be a useful support for explaining the roles of each temple in the G group not only to specialized scholars, but possibly also to non-expert people like students or common visitors.

Differently from the reality-based models, the archetypal reconstructive digital models present very different purposes (Frischer et al., 2002; Beyond Illustration, 2008; Rua and Alvito, 2011). Thanks to the virtual representations of the current and reconstructed temples, an effective diachronic analysis becomes possible, stacking on the possibility to "see" what in the last few years was possible to be figured out only through written descriptions or rough drawings (El-Hakim et al., 2008).

The path from reality-based to interpretative models is not so widely developed as the conventional modeling from real data (Russo and Guidi, 2011). In this case, besides the particular attention given to the integration between 3D surveyed data and historical sources, a precise iterative feedback strategy was defined in order to check each important interpretative step during the virtual reconstruction. This procedure was based on a sequence of archeologist's controls on the modeling evolution, starting from a volumetric simplified version to the best detailed one. The application of this approach should allow to reach a better shared solution between 3D starting data, historical sources and archeological knowledge, exploiting a strong interaction between historical and technological experts.

For the whole process different software were used (Cyclone, Geomagic, Polyworks, Rapidform, Modo) in order to get the best functionalities from each of the mentioned systems.

3. Survey

3.1. Planning

As known several factors may affect the quality of 3D data acquired by a range device (Fig. 1). Equipment choices, logistics and environmental conditions have to be considered in a survey planning, especially when operating in the middle of a forest, like

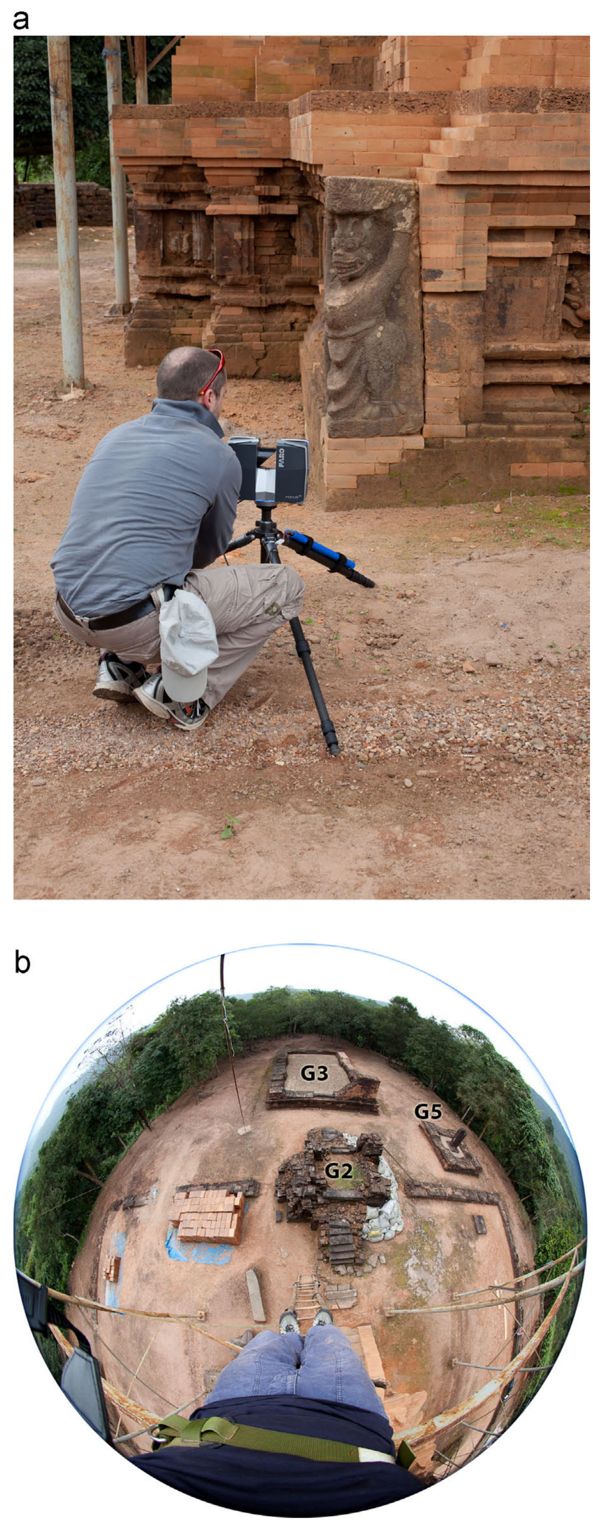

Fig. 1. Different 2D and 3D image acquisition steps: (a) 3D survey acquisition of the decorated basement; (b) fisheye image of G2, G3 and G5, taken from the structure covering the main temple (Kalan).

Fig. 2. Handmade structures arranged on the field by local workers for locating the laser scanner in the appropriate positions: (a) mounting the platform on the top of the structure surrounding the Kalan; (b) laser scanner located on the platform at 7 m above the ruins; (c) multi-section ladder for reaching the platform; and (d) structure for elevating the scanner at 3 m from ground. During 3D acquisition the operator lies in the blind cone below the scanner in order to avoid the laser beam trajectory.

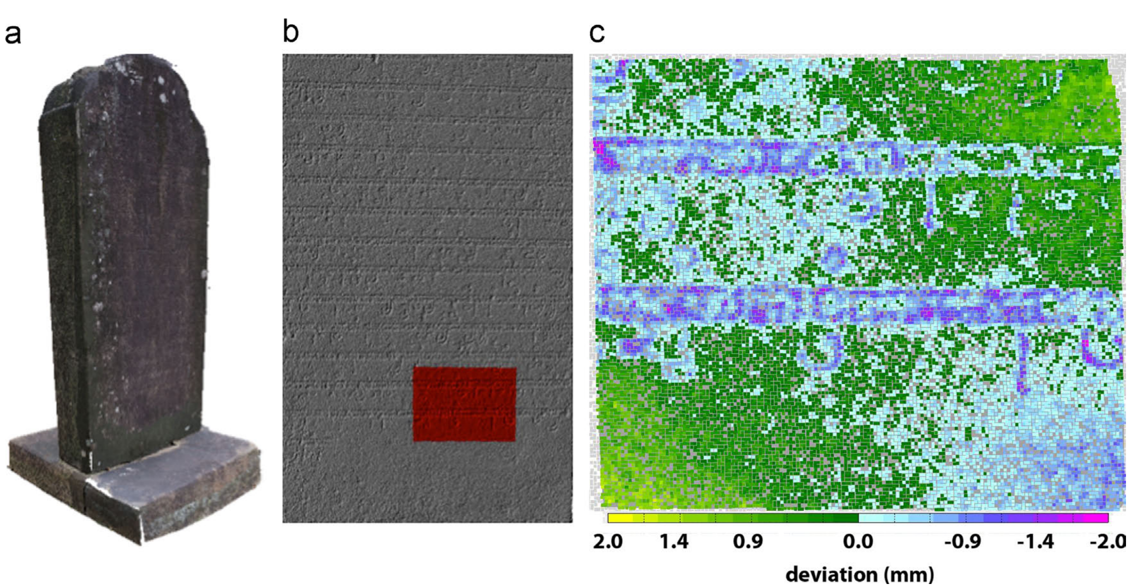

Fig. 3. High resolution capture of the foundation stone through SFM: (a) texturized 3D model measured through a sequence of 24 images shot around the artifact; (b) mesh model of the central part of the stone with a small area highlighted in red; (c) color-coded deviations of the SFM acquired points from a best-fitting plane calculated on the red area of (b), clearly showing the nearly 2 mm carving on the stone.

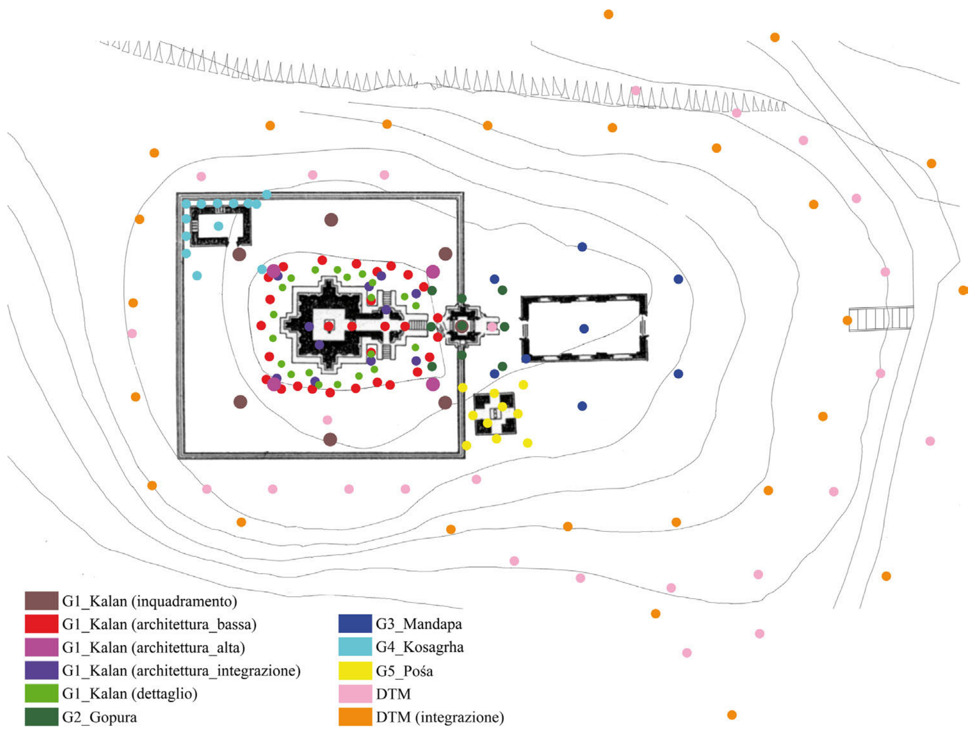

Fig. 4. Network of the 3D laser scanner positions all over the archeological area containing the G Group.

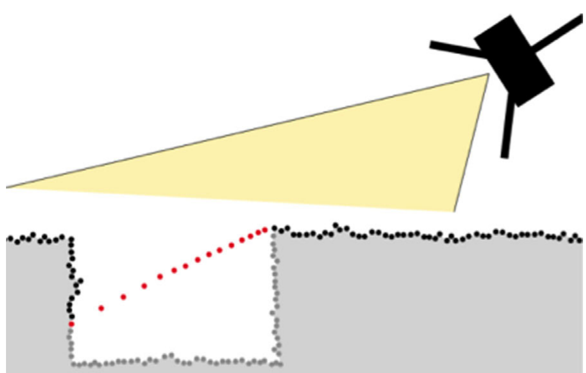

Fig. 5. Tangential edge error in 3D point clouds: the red points represent the incorrect data with respect to the real ones (black-grey color).

in this specific case. An accurate evaluation of such factors allows optimizing the 3D acquisition, minimizing possible problems that can occur during the survey. In addition logistics and weather conditions become crucial specially if the survey project has to be planned abroad, with no possibility to travel back and forth to the lab, and little or no possibility to lose operating days for possible logistic delays (such as for example days or weeks lost for custom controls, typical when instrumentation is sent trough a courier), or on the field, due to bad weather conditions.

The range sensing technology chosen for this project was Continuous Wave (CW) laser scanning with detection of phase deviation. This is now implemented in several devices from the major manufacturers, including the relatively new 3D lasers scanner from Faro: the Focus3D system. This choice was made because it appears very suitable for short–middle ranges in terms of tradeoff between precision (around 2 mm standard deviation tested on a planar target located at 20 m from the instrument), working speed (1 million points per second max), equipment weight and size (5 kg of material fitting in a small bag, compliant with airlines standards for hand-luggage), and, last but not least, a cost definitely lower than other analogous products on the market.

Before starting the project a few considerations have been made about the possibility to use “Structure From Motion” (SFM) as an alternative to laser scanner, being nowadays a powerful tool for generating textured point clouds. The advantage would have been to limit the amount of equipment to carry from the lab, consisting of just a camera, a tripod and a PC for checking the data. At the moment of project planning (December 2010) such technologies were very promising but not yet developed as today (October 2012). As a consequence the choice was, as often happens in projects where the site to be digitized is not easily reachable, to get redundant 3D information from multiple sensors. Therefore it was decided to carry to the archeological site both the equipment needed for laser scanning and SFM image processing. Laser scanning was the main tool being metrical, reliable, and already used by the authors in plenty of other projects, while image processing was only experimented on the site with a few datasets. For all these reasons in addition to the above mentioned laser scanner from Faro, a Canon 5D Mark II digital camera was delivered to the excavated area.

Before leaving for the acquisition campaign, the scanner performances were accurately tested in laboratory, verifying the data quality, reliability and ideal working distance. A similar performance test was repeated on the archeological site, verifying the real behavior of the electronic and optical system with high temperature and extreme humidity condition, using the actual surfaces of the monument as test objects. Different instrument set-ups were then defined, connecting a set of distances with relative 3D scanner performances (see Table 1).

The archeological plan was examined in order to suggest a first optimized network of scan positions, trying both to minimize the acquisition time and to consider all the morphological characteristics of the architectural examples.

The 3D survey of the area was planned following three different steps. In the first one all the architectures were acquired, adapting the number of scans and working distance set-up to the different levels of geometrical complexity of every single ruin. For the main temple (Kalan) the level of morphological complexity led to a multi-resolution approach in order to survey the whole structure, the different bricks carvings and the sculpted decorations. In addition the terrain morphology and the presence of vegetation were carefully taken into account. The sum of these factors led to begin from the architectonical survey instead of DTM, in order to minimize the generation of possible aligning errors due to the sliding effect of a huge number of scans required to fill the great number of shadows of the DTM area. For this reason the first central block of the area was represented by the Kalan, in which the richness of 3D features and its closed shape was essential to define a point cloud alignment with an acceptable accuracy level.

In addition a sequence of DTM point clouds, aligned in the same reference system of the Kalan, was acquired, generating a first DTM reference area. Afterwards the remaining part of the DTM was scanned and aligned to the Kalan range maps. In the same time the 3D acquisition campaign of the other different monuments was carried out, aligning and creating self-consistent point clouds models. Finally those data were aligned in a common reference system using the DTM raw representations of the buildings.

3.2. 3D data acquisition

The survey of G Area regarded both the 3D geometrical acquisition of five different architectures with associated findings and the 2D image acquisition for texture and environment documentation.

In this phase a dedicated 3D acquisition of the upper part of the Kalan was carried out, in order to scan all the hidden area of this complex geometry. The scanner was positioned at 7 m from ground in the four corners of the iron structure covering the Temple, acquiring 4 high resolution scans of the whole architecture and the surrounding DTM area. Then a long sequence of architectonic acquisitions was realized around the building and integrated with a detailed one devoted to survey the decorated basement. To avoid the shadow effects generated from the basement, an additional sequence of 3 m height scans was carried out. Locating the laser scanner in the needed position around the main temple (i.e. the taller ruin of the group) was a crucial point for avoiding lacks in the final survey. Such activity was made possible thanks to the small size and low weight of the chosen instrument, together with the prompt and proactive collaboration of the local personnel involved in the site maintenance, that provided to cobble together structures apparently unsafe but actually very solid and functional to the purpose, like those shown in Fig. 2. In this way nearly any needed capturing position in the 3D space around the building was properly reached.

The second step consisted of the DTM acquisition for creating a geometrical framework in order to locate the whole architectures in a common reference system. For this reason a wider surface respect to the archeological area was considered, in order to acquire part of the morphological terrain context. During Kalan and DTM acquisition a raw alignment phase was also pursued, in order to verify the presence of lacks in the 3D survey. Thanks to this step, an integrative campaign was planned at the end of the first acquisition stage, scanning all the incomplete areas. The other architectural buildings presented a simpler geometry or fewer decorative portions than the Kalan example, for this reason a simpler acquisition process was adopted, using only the medium resolution set-up, integrated by some special scans for better covering the worst preserved portions.

The last phase focused on the 3D acquisition of some archeological artifacts that were found during the excavation of the G Area and were then classified inside the store-room of the local museum. This step was planned both to store digitally these important sources and to create 3D models of decorations that could be re-positioned afterwards on the virtual architectures. For this task a precise survey set was defined, in order to optimize the geometrical resolution coherently with the formal complexity of the sculpted finds. A summary of the laser scanner settings used in the different phases is reported in Table 2.

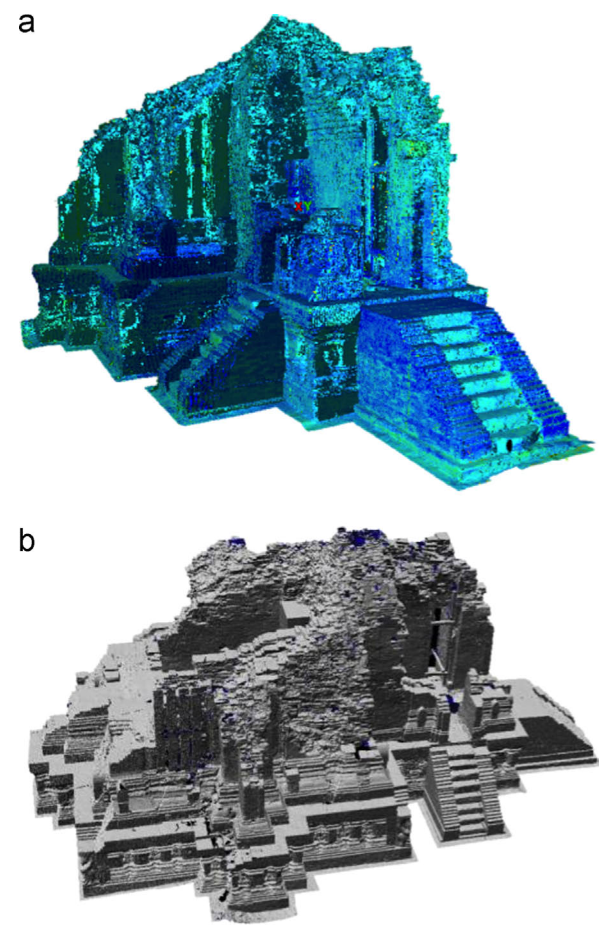

Fig. 6. (a) Point cloud model of the Kalan cleaned and aligned in the same reference system; (b) polygonal model of the Kalan with a decimated and watertight mesh.

The photographic campaign was devoted to the acquisition of

(i) architectonic images for texturing projection purposes;
(ii) detailed images for the creation of seamless texturing patterns;
(iii) panoramic images to gather a believable representation of the surrounding environment through the stitching of multiple fish-eye photographies; and
(iv) few image sets taken around four monuments for experimenting Structure From Motion (SFM) techniques.

The main difficulty with these latter images was related to the presence of architectural elements inside dense vegetation, slightly moving due to wind, that involved the presence of images difficult to match each other, with SFM results not always good.

However, in a few cases the results of the SFM tests gave very good results, as for example for the 3D capture of the G5 temple. The example was chosen for the presence of a Sanskrit inscription on the foundation stone whose carving depth is in the order of a few millimeters. While the laser scanner measurement uncertainty in the order of 2–4 mm (depending on the scanned material) made it impossible for the readability of such tiny geometric detail, an appropriate SFM processing produced a very accurate detection on the carved inscription, as shown in Fig. 3.

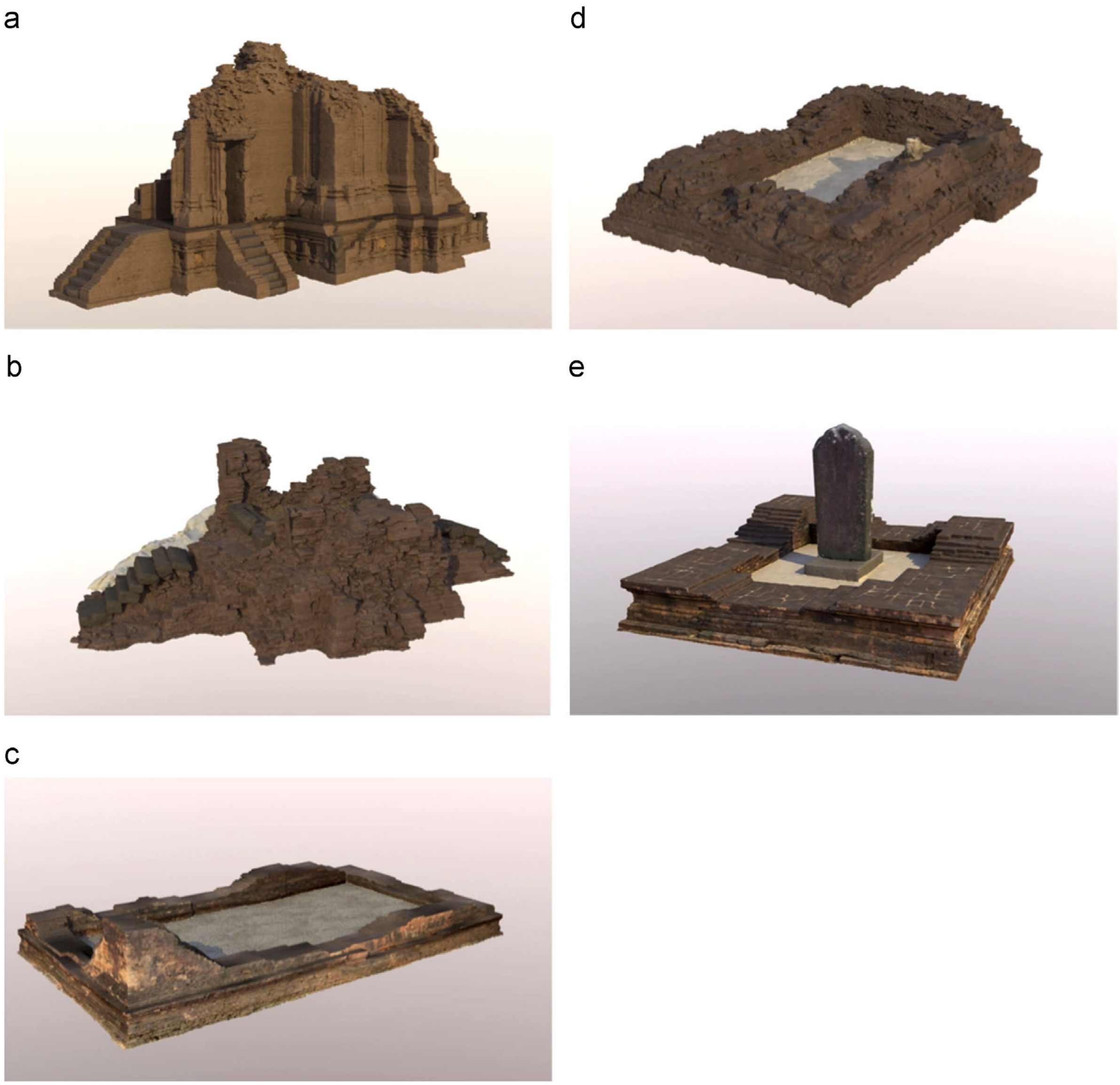

Fig. 7. Reality-based models of all ruins in the G group obtained from 3D data generated by a laser scanner at 1 cm resolution and texturized with the actual images of the buildings: (a) G1, the main temple; (b) G2, the entrance portal to the holy area; (c) G3, the assembly hall; (d) G4, the south building; and (e) G5; the kiosk of the foundation stone.

The result here was generated by processing 24 images 21 megapixels each, taken with a 20 mm lens and the camera at about 3 m from the artifact, with the open source software developed by the Institut Géographique National (IGN) in Paris, with the "Apero" module for orienting the shots (Pierrot-Deseilligny and Cléry, 2011), and the "Micmac" module for generating the colored cloud of points. The result was then made metric evaluating a scale factor respect to the laser scanning of the same structure.

3.3. *Digital data management*

A database structure was created to store this huge amount of 2D and 3D images adding some useful information like date, size and scanner set-up. This allowed to easily manage such information even if not processed immediately. The database was integrated with the reference plan shown in Fig. 4, where all the scanner positions were annotated during the survey. These supports allowed to carefully plan and manage the whole 3D scanning campaign, avoiding the post-processing of excessive amounts of data that a device capable to generate 1 million of Points/s might easily produce.

4. Reality-based modeling

The only drawback of the compact scanner employed in this project was the generation of non-existing points in correspondence of the building edges, when the acquired surfaces were too much tangential with respect to the laser beam as shown in Fig. 5. For this reason, although some automatic filtering allowed reducing this effect, before starting the point cloud alignment process a considerable amount of manual preprocessing for deleting outliers was needed.

Every cleaned scan was then aligned by means of the ICP algorithm implemented in the Leica Cyclone 3D processing software in order to position the point clouds of each ruin in the same reference system. The resulting point clouds were then decimated at 1 cm sampling step, leveling all the over-sampled portion of the architecture and lowering the amount of 3D data. Each point cloud was subdivided in sub-units whose size was limited to 3 million of points in order to make the following meshing step easier and more controllable. Such subdivision did not follow a semantic thinking because the principal aim was just the identification of area suitable to be closed afterwards with a polygonal post-

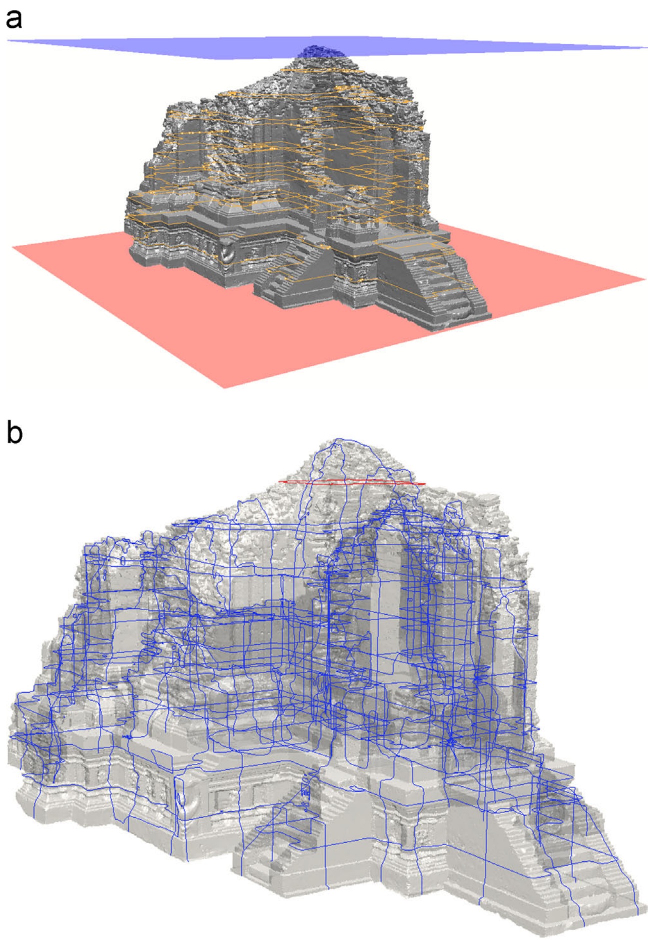

Fig. 8. Extraction of planar sections on the reality-based 3D model of the Kalan as starting elements of the building digital reconstruction: (a) horizontal sections (*xy* plane); (b) vertical section (*xz* and *yz* planes).

processing. Every sub-scan was then meshed uniformly. However the resulting high-resolution polygonal models presented both several topological errors, due to residual errors that survived during the cleaning phase, and a huge numbers of holes, related to the shadow effects of the complex geometry.

All these holes were closed with a manual identification process, choosing for every single hole the best closing algorithm. This long process was considered for the different characteristics of the holes related to the dimensions, the position with respect to the model (flat plane, edge, corner, etc.) and the complexity of the polygons in the border. An automatic or semi-automatic approach would have risked neglecting these differences, generating non-reliable portions in the reality-based model.

These conditions have been critical in particular with not well-preserved buildings; in that case a rather long post-processing phase was faced to generate a watertight polygonal model. This stage allowed to build the 1 cm resolution geometry of all the five buildings in the G Area, a 10 cm resolution DTM of the hill where G Area is located, a set of polygonal models of sculpted finds with a geometrical resolution of 2 mm (Fig. 6).

At the end different approaches were followed to texturize such reality based models. As shown in Fig. 7 the models representing the worst conserved buildings, like G2 and G4, a seamless shading pattern originated from real images which was chosen as the most practical way to achieve a believable result (Fig. 7b and d respectively). For the Kalan temple and for the well-preserved architecture, such as G3 and G5 (Fig. 7c and e respectively), most of the texturing was done with the actual images of the ruins projected on the model, with the integration of seamless shading patterns for the less characterized components. In the latter case such integration was particularly extended, texturing with projected images the stela and the lateral walls, with uniform seamless patterns the central stone basement and the sand surrounding it, and with a non-uniform pattern the upper faces of the joints between the tiles.

In addition to the single texturized models, the 3D modeling of the whole scene used the low resolution model of the DTM, some

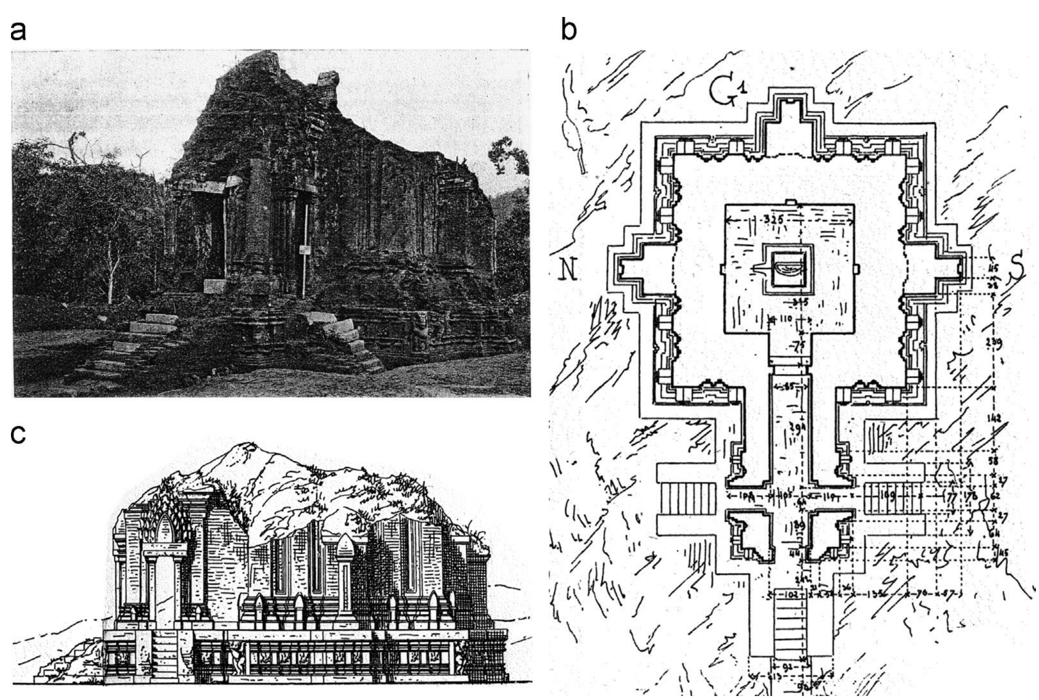

Fig. 9. Documentation of the Kalan in the G Group, collected by Hanri Parmentier at the beginning on '900: (a) photography of the temple in a conservation state better than the current one; (b) upper view; and (c) lateral view. The latter drawing was particularly useful for guessing location and shape of the niches above the doors.

library models of trees similar to the ones grown in that part of the forest, and a spherical panorama captured from the top of the structure covering the kalan, re-projected on a spherical surface surrounding the area, as shown in Fig. 18a.

The approach followed for acquisition and modeling of the sculpted findings was in principle similar to that employed for the architectural structures, with a change in terms of geometrical resolution settings for the Faro Focus3D scanner. Such equipment showed a fairly good capability to reproduce thin details in the final polygonal model. For these reasons an optimized post-processing procedure was analyzed to preserve such useful geometrical information. The models obtained from this process gave a set of reality based mesh models optimized for preserving thin geometric details, finalized to the decoration of the reconstructed geometrical models.

5. Reconstructive modeling

The reconstruction phase started from the geometrical information contained in the reality-based models of both the single buildings and the whole aligned scene, from which a first set of objective geometrical constraints were extracted by sectioning the digital artifact with planes along the three main directions *x*, *y* and *z* (Fig. 8).

In this way the accurate building footprints, the height of architectural elements still standing, the positioning of niches for decorations etc. were determined according to their actual configuration for driving the progressive 3D reconstruction phase. The reality-based digital model was also used for checking the coherence of each reconstructive step. The digitally reconstructed models were continuously compared with the reality-based models, in order to verify possible incoherencies introduced during the reconstruction procedure. In addition to such geometrical constraints, the creation of reconstructive models was also based on the integration between bibliographical or iconographical sources (Pierrot-Deseilligny and Cléry, 2011; De Lajonquère, 1902–1912; Finot, 1904; Parmentier, 1909) and acquired 3D data.

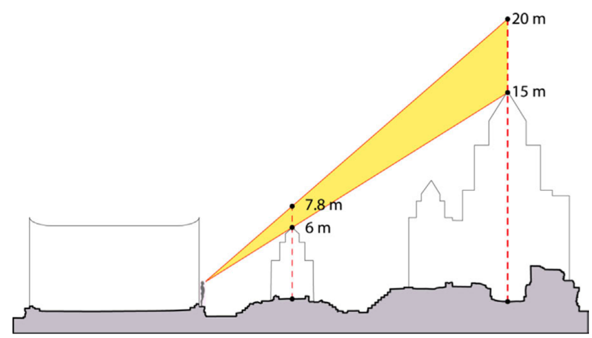

Fig. 11. Height analysis based on religious considerations according to which a monk of the group accompanying the Brahmin should have remained in the assembly hall and from that point of view the main temple (G1) should have been hidden by the portal (G2).

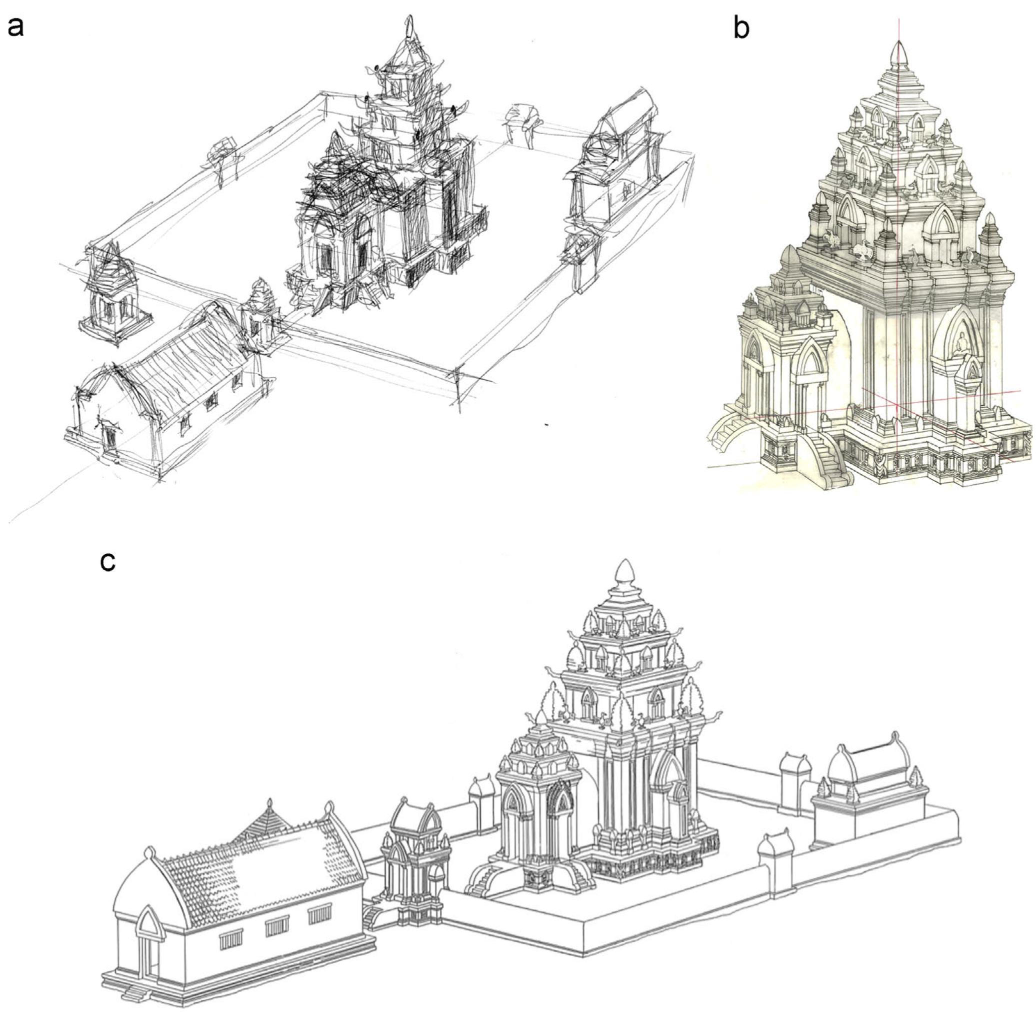

Fig. 10. Envisioning of G group by Pierre Pichard: (a) preliminary sketch of the whole area; (b) detailed hypothesis of the Kalan structure; and (c) refined hypothesis of the whole group.

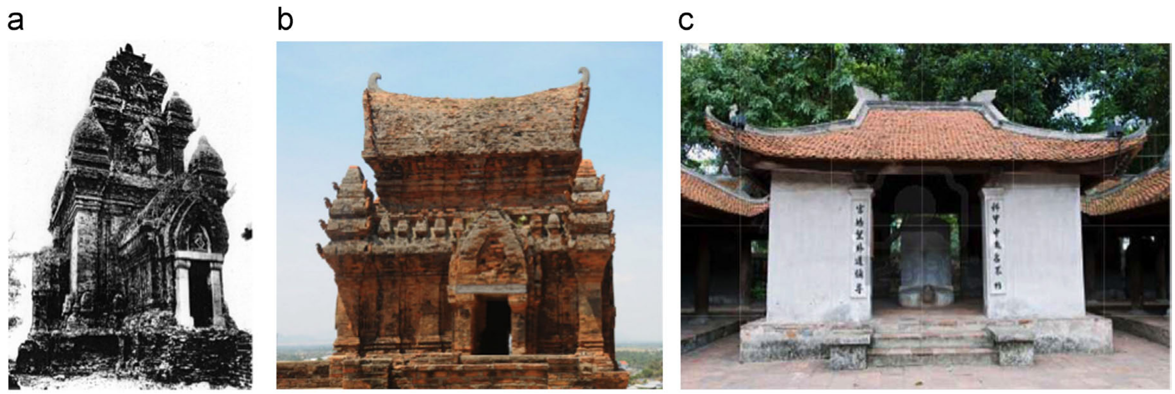

Fig. 12. Examples of reference for finding possible structural and decorative elements not attainable from the geometrical survey and the historical documents referred to the in G Group of MySon: (a) roof decorations of the Kalan in Po Klaung Garai; (b) roof decorations for G4; and (c) kiosk for a foundation stone close to Hanoi.

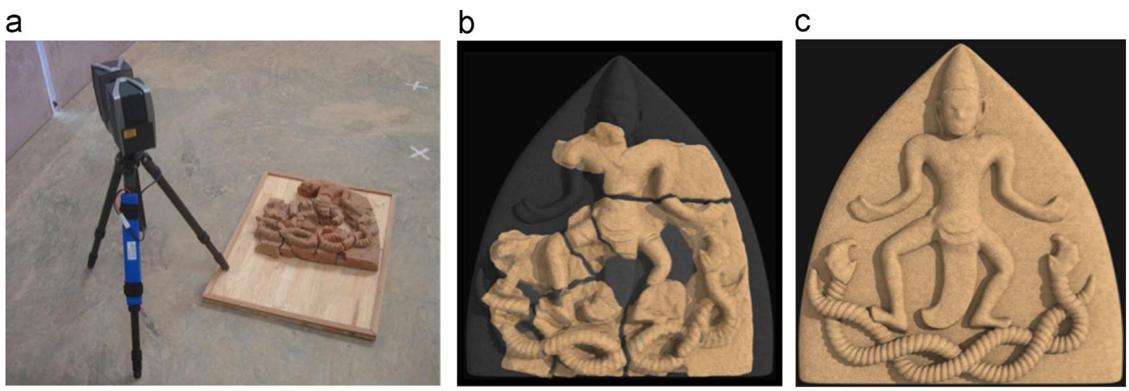

Fig. 13. Sculpted tympanum representing Krishna dancing on the snakes, originally at the entrance of the Kalan: (a) 3D laser scanning in the "store room" of the museum; (b) reality-based model from the 3D data; and (c) digital reconstruction of the lacking parts.

As the main source the extensive documentation work done by Henri Parmentier at the beginning of '900 on the whole area was analyzed. Parmentier produced some nice shots of the Kalan after its first discovery (i.e. in a better conservation state than the current one) as shown in Fig. 9a. As any French Archeologist of the period he was also very much used to drawing each ruin, trying to highlight both the lost parts of the buildings and some interpretative reconstructive hypotheses (Fig. 9b and c). To verify this historical source and fill some remaining lacking elements, a further iconographical research was done, researching the common stylistic elements present in other coeval Cham's architectures.

In order to complete this comparison, the interpretative drawings from Pierre Pichard, one of the most known experts of Cham architecture were also used (see Fig. 10), containing many elements that have been used in the final model.

But, according to other big experts of Indochinese archeology as Patrizia Zolese and Mara Landoni, authors of last excavations on the G Group, a few points were controversial, like for example the height of the building, or the shape of the portal roof, since no suggestion of that kind came by the excavated materials (Hardy et al., 2009). No information was found in the historical sources, and for this reason a comparative analysis with other contemporary and better-preserved architectures was carried out, together with an estimation of the volume of debris found during the excavation phase. Finally a building height in the range from 15 to 20 m was agreed by the experts as suitable for the Kalan temple.

In addition to this rough approximation, the religious role of each building was considered for refining the Kalan height estimation. During the religious ceremony the young Monks accompanying the Brahmin during his journey to God (that for the Hindu religion is inside the Kalan) enter into the assembly hall and stop there, leaving the Brahmin alone to enter into the holy enclosure from the portal (G2). For this reason the gateway entrance door surely prevented to see the holiest building, i.e. the Kalan. This consideration, explained graphically in Fig. 11, allowed to define a believable dimensional range for the Kalan and the gateway, identifying 7 m as suitable hypothesis for the gateway height and 16 for the Kalan.

The central position of the Kalan Temple in the Cham's culture has allowed to find a big amount of iconographical and historical data related to Kalan Temples, while fewer information was collected for the secondary buildings like the gateway (G2), the assembly hall (G3) and the south building.

For this lack the shape of the decorative elements in the corners of the Kalan roof was inspired by the Kalan temple in Po Klaung Garai (Fig. 12a), the roof decoration in G4 from the building in Fig. 12b. Finally the reconstruction of the pavilion for the foundation stone has been quite complex; the research was extended to other religious areas (not only archeological one) in order to find some dimensional information that could support the digital reconstruction, finding an interesting similarity in a kiosk containing a stone turtle (shown in Fig. 12c) in the area of the "Quoc Tu Giam" or Temple of Literature, close to Hanoi.

As for the architecture the decorative elements for the reconstructed buildings have also been created starting from the 3D laser scans of some decorative elements found during the archeological excavations in the G Group now conserved in the "store room" of the MySon museum. For some pieces it was necessary for a redrawing due to the presence of broken elements, like for example the Krishna in Fig. 13.

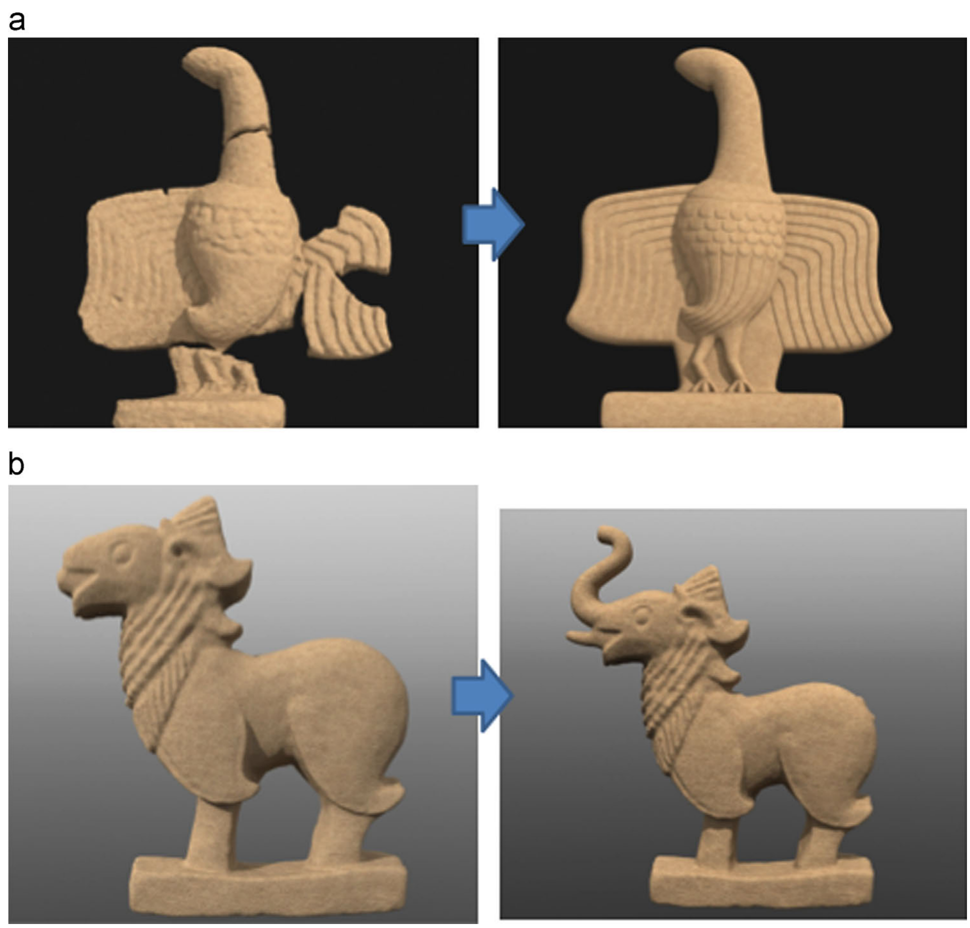

Fig. 14. Reconstruction of decorating items originally on the Kalan roof: (a) Hamsa, a kind of holy goose; (b) Gajashimha, the crossbreed between a lion and an elephant. Especially in this latter case the reconstruction was a crucial step for making recognizable the Elephant element otherwise disappeared in the archeological find.

Fig. 15. Example of remodeling of one of the kalas, decorating items originally located in niches carved in the bricks all around the lower part of the Kalan. Although the shape was recognizable also in the left model, the number of polygons of the right regularized model is approximately ten times lower.

In this step the archeologist's feedback was necessary to suggest the virtual reconstruction of some lacking parts, which was hypothesized coherently with the iconographical sources.

The same reconstruction stage was made also on several other decorations as for example those found on the roof of Cham. As shown in Fig. 14, recovering the shape of the Hamsa wing (a kind of holy goose), broken before its finding, or the proboscis of a Gajashimha, the crossbreed between a lion and an elephant, was a way for making recognizable the digital models of such iconic objects.

In addition, even when the original piece, and therefore the related mesh, was not so altered respect to its supposed original shape (see for example Fig. 15) we decided to remodel the mesh. The main reason in these cases was the optimization in the number of polygons necessary for avoiding decorated models made by an extraordinarily high number of polygons, with

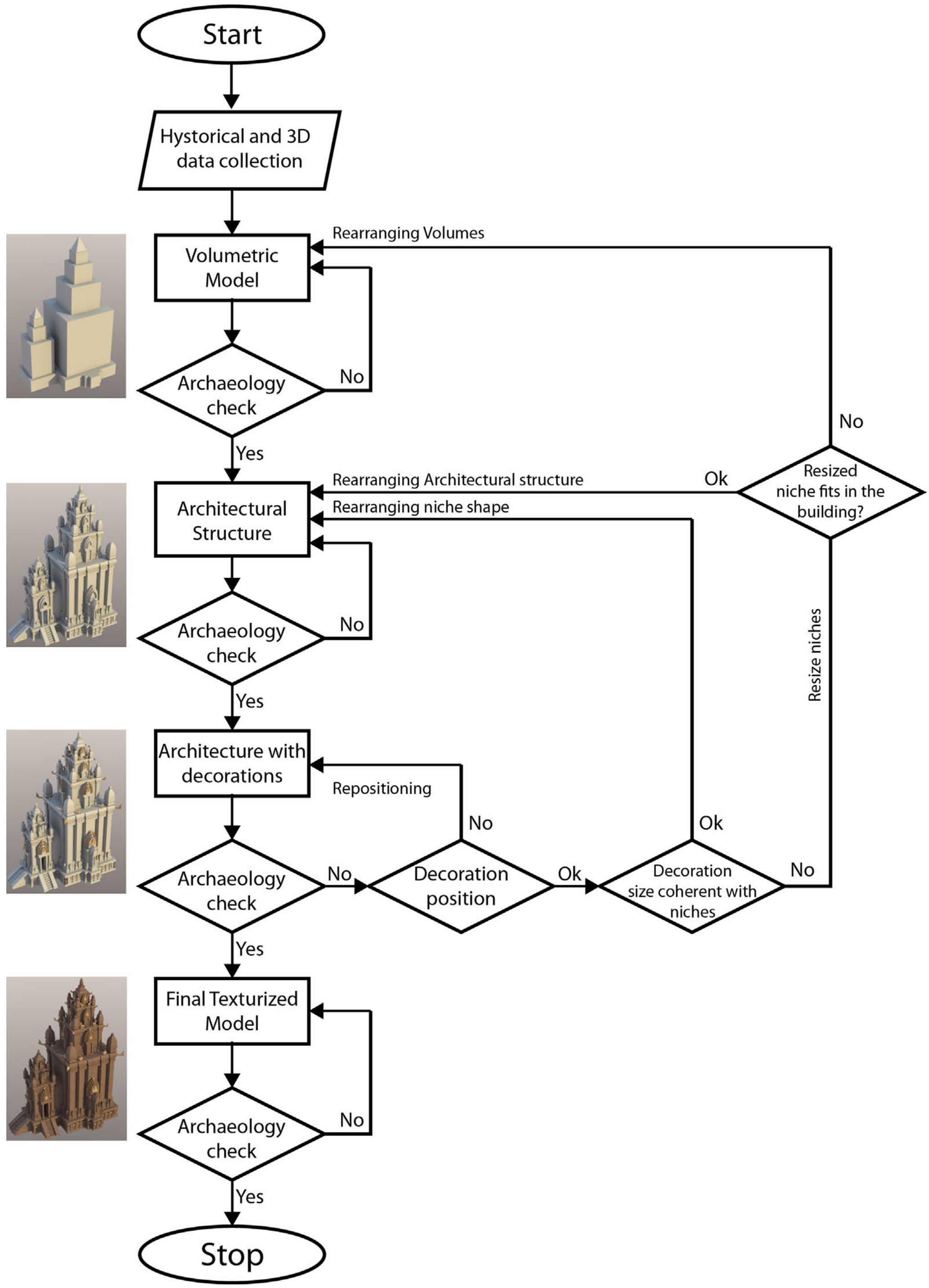

Fig. 16. Four stages iterative feedback process used for reaching a reasonable reconstruction of the temples in the G Group.

consequent waste of time for rendering and manipulating the final reconstructed model.

The final step of this work was the reconstruction of the architectural structures starting from the existing geometry. The approach used was to interleave a phase of technical construction of the shapes with a strong critical revision by the experts of Cham archeology (primarily Patrizia Zolese from Lerici Fundation) for generating feedback and corrections before moving forward to the following step, possibly iterating the construction/correction loop as much as needed.

In Fig. 16 such approach is shown with reference to the Kalan, but the same work was carried out for each of the buildings belonging to the G Group. Following the flow diagram from top it is shown that the volumetric model of each building was initially built integrating the sections extracted from the acquired 3D models with other information coming from the sources.

Such proportions, mentioned above with the considerations made in Fig. 11, allowed to start analyzing a more detailed stage leading to the second "revision loop" shown in Fig. 16, where every architecture was refined, carving the virtual walls with hypothetical pilasters and niches. The introduction of these elements was quite complex for the very little information coming from the ruins. The comparison with similar stylistic elements in other Cham buildings all over the country was

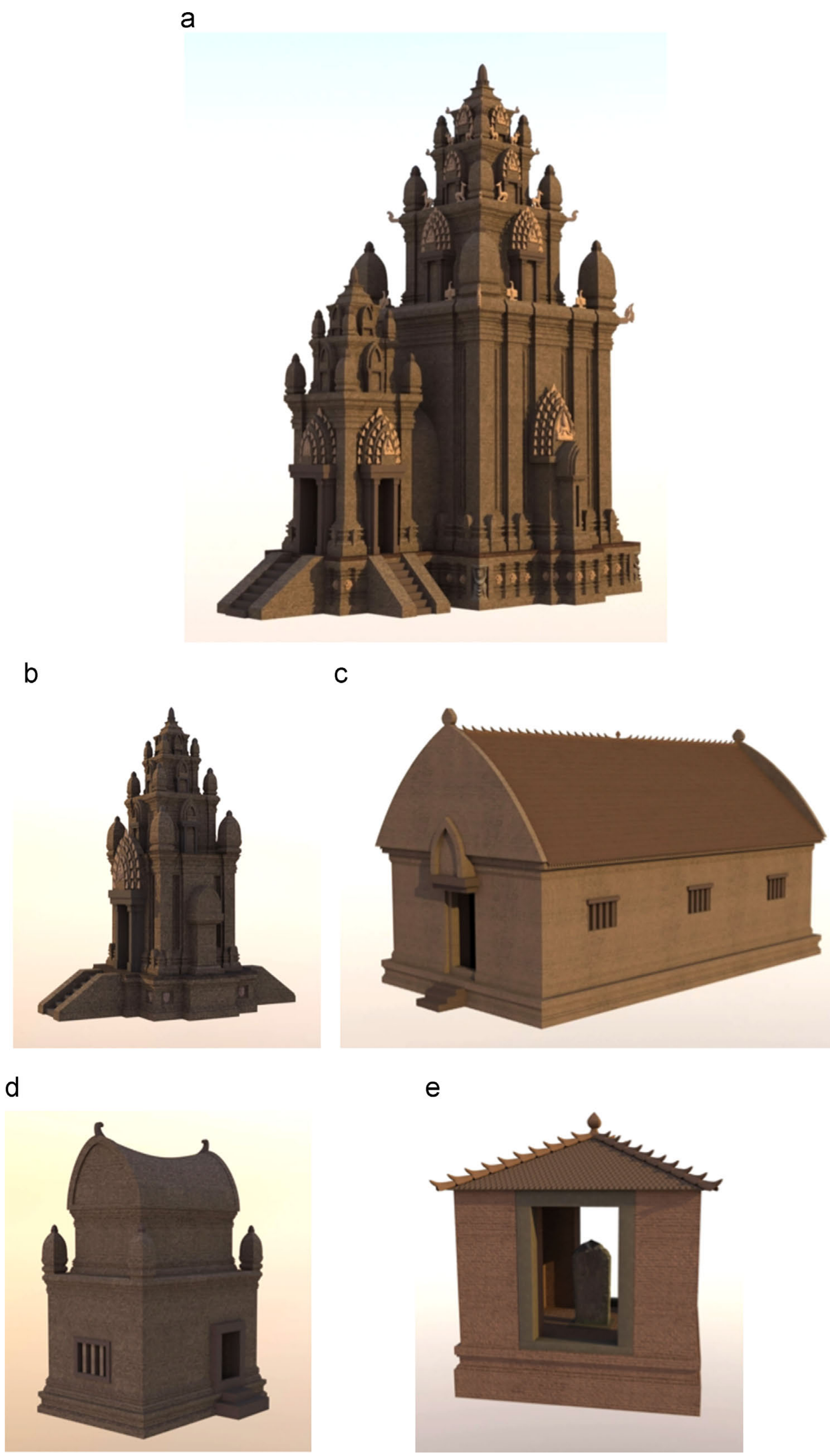

Fig. 17. Reconstructed models of temples in the G group: (a) G1, the main temple; (b) G2, the entrance portal to the holy area; (c) G3, the assembly hall; (d) G4, the south building; and (e) G5; the kiosk of the foundation stone.

essential at this stage in order to identify common structural patterns, which have been afterwards adapted to other G buildings (Fig. 17).

In the following modeling step, illustrated in the third "revision loop" in Fig. 16, the latest architectonic refinements were applied and all the sculpted decorations digitized in the store-room were

Fig. 18. Modeling of the whole G Group area, including the terrain and the surroundings: (a) reality-based model, as it is in the current days; (b) reconstruction as it was supposed to be 500 years ago.

located in the supposed right places. The introduction of these decorations constrained the architecture structure, trying to fit them in their hypothesized positions. In this last passage the modeling level led to such an advanced level of detail that even the experts demonstrated doubts and decided not to introduce unknown elements inside the architecture, leaving intentionally some informative lacks on the reconstructive models.

In the final step (fourth "revision loop" in Fig. 16) the different texture mapped architectural models, including all their decorations, were merged in a single three-dimensional virtual reproduction of the G group.

The environment was finally added as in the reality-based case mapping a panoramic view of the true surroundings on a sphere containing the whole model and adding 3D models of vegetation

Video S1. Video of 3D Model 1: The final “Kalan” temple (G1), digitally reconstructed according to the methodology described in the paper, is shown here in a panoramic view, surrounded by the other reconstructed accessory buildings (G2, G3, G4, G5). All are immersed in a virtual environment generated by a fish-eye panoramic view of the real Group G, shot during the survey. The model shows a 3D model of the “Kalan” temple (G1), showing the articulated sculpted decorations on the building. Such decorations are in part still present on the ruins, but a large part of them has been 3D acquired in the local museum deposit and virtually re-positioned in the original place. The model inside as well as the exterior part, up to the inner cell, the most sacred zone of the whole area, whose access was reserved to the Brahmin, has been modeled. Supplementary material related to this article can be found online.

to the true DTM, leading to the final reconstructive view as shown in Fig. 18b. See Video S1 for a sequence of such panoramic view, with the camera turning around the reconstructed temple.

6. Conclusions

This paper describes a process of acquisition and modeling applied to create a virtual reconstruction of lost architectures located in a striking context, the Mỹ Sơn archeological area in Vietnam. A commonly used 3D acquisition and modeling approach along with some different topics are discussed, suggesting both optimized procedures for data processing and communication. In particular, as synthesized in Fig. 16, an iterative methodology is suggested to support the interpretative modeling step, simplifying the feedback on virtual models by the archeologists. This solution gives a significant improvement on the complex procedure for reconstructing in 3D an ancient building whose remains are often very few with respect to its original shape. In this way both an instrument of communication and valorization of the cultural heritage site is provided, helping the interpretation of archeological and architectural ruins. As future development it would be interesting to explore an enhanced communication level between the different historical and technological experts, based on social networking instruments, and annotations on renderings or directly on 3D models.

Appendix A. Supplementary Information

Supplementary data associated with this article can be found in the online version.

References

Bernardini, F., Rushmeier, H., 2002. The 3D model acquisition pipeline. Comput. Graph. Forum 21 (2), 149–172.

Beraldin, J.A., Picard, M., El-Hakim, S.F., Godin, G., Valzano, V., Bandiera, A., et al., 2002. Virtualizing a byzantine crypt by combining high-resolution textures with laser scanner 3D data. In: Proceedings of VSMM2002, Gyeongju, Korea, pp. 3–14.

Beyond Illustration, 2008. In: Frischer, Bernard, Dakouri-Hild, Anastasia (Eds.), 2D and 3D Digital Technologies as Tools for Discovery in Archaeology. Archaeopress, Oxford

De Lajonquère, E.L., 1902–1912. Inventaire archéologique de l’Indochine, vol. 3, Paris.

El-Hakim, S., Beraldin, J.A., Picard, M., Cournoyer, L., 2008. Surface reconstruction of large complex structures from mixed range data – the erechtheion experience. In: Proceedings of XXI Congress of the International Society for Photogrammetry and Remote Sensing (ISPRS), vol. 37, Beijing, China, pp. 1077–1082.

El-Hakim, S., Lapointe, J., Whiting, E., 2008. Digital reconstruction and 4D presentation through time. In: Proceedings of the International Conference on Computer Graphics and Interactive Techniques (SIGGRAPH), Los Angeles, California.

Finot, L., 1904. Notes d'épigraphie: XI. Les inscriptions de Mi-Son. In: Bulletin de l’Ecole française d’Extrême-Orient, tome 4, pp. 897–977.

Frischer, B., Niccolucci, F., Ryan, N., Barceló, J.A., 2002. From CVR to CVRO: the past, present and future of cultural virtual reality. In: Proceedings of the VAST EuroConference, Arezzo, Italy, pp. 1–12.

Guidi, G., Russo, M., Beraldin, J.-A., 2010. Acquisizione e modellazione poligonale. McGraw Hill, Milan.

Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A., Ercoli, S., 2009. A multi-resolution methodology for the 3D modeling of large and complex archeological areas. Int. J. Archit. Comput. (IJAC) 7 (1), 39–55 (special issue).

Hardy, A., Cucarzi, M., Zolese, P., 2009. Champa and the Archaeology of Mỹ Sơn (Vietnam). NUS Press, Singapore.

Ky Phuong, T., Rejniewicz, L., Drygallo, R., Kwiatkowski, K., 1990. Récherches sur les Monuments du Champa. Interim Report de la Mission polono-vietnamienne. PKZ (Eds.), vol. 1, Varsovie.

Levoy, M., Pulli, K., Curless, B., Rusinkiewicz, S., Koller, D., Pereira, L. et al., 2000. The Digital Michelangelo Project: 3D scanning of large statues. In: Proceedings of ACM SIGGRAPH, pp. 131–144.

Pierrot-Deseilligny, M., Cléry, I., 2011. APERO, an open source bundle adjustment software for automatic calibration and orientation of a set of images. In: Proceedings of the ISPRS Commission V Symposium, Image Engineering and Vision Metrology, Trento, Italy, 2–4 March.

Parmentier, H., 1909. Inventaire descriptif des Monuments Cams de l'Annam, tome II, Imprimerie Nationale, Paris.
Remondino, F., 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. Remote Sens. 3 (6), 1104–1138.
Rua, H., Alvito, P., 2011. Living the past: 3D models, virtual reality and game engines as tools for supporting archaeology and the reconstruction of cultural heritage – the case-study of the Roman villa of Casal de Freiria. J. Archaeol. Sci. 38 (12), 3296–3308.
Russo, M., Guidi, G., 2011. Reality-based and reconstructive models: digital media for cultural heritage valorization. In: SCIentific RESearch and Information Technology (SCIRES-IT), vol. 2 (4), CASPUR-CIBER Publishing.