Title: The leading fusion of Laser scanning and Close range Photogrammetry
Subtitle: Laser-Photogrammetric mapping of Bam Citadel (Arg-E-Bam)

Abstract

In the last days of the year 2003 a terrible earth quake afflicted Bam, Iran, (26.12.2003, 6.3 Richter Scale) leaving behind more than 50,000 casualties.
Invited by the Iranian Cultural Heritage Organisation ICHO [www.iranmiras.org], Riegl LMS GmbH /Austria [www.riegl.com] and their Iranian agent, NPR Co. [www.nprco.com] performed a 3D-mapping of the greatest mud-brick and adobe complex of the world, the ancient Citadel of Bam (Arg-E-Bam), making use of a unique system integration of close range photogrammetry and laser scanning technology. The impressive results of the scanning campaign prove this method a highly efficient bi-technique whose capacities have yet to be fully discovered and exploited.

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Intro

The historic monument of Bam consists of a town, Ame – Neshin, and a protruding ruler's palace, Hakem – Neshin, both entirely built from mud bricks, clay, straw and palm-tree trunks. Covering a terrain of 20,000m^2, the Citadel of Bam is known as the largest mud-brick and adobe complex of the world, thus a site of strong interest for UNESCO and ICHO who is in charge of restoration, preservation, historical and archaeological research as well as surveying and documentation of Iranian historical sites.
Intensive restoration works of the Bam Citadel have been carried out continuously since 1953. After the earthquake, organising humanitarian help for the inhabitants of Bam required, of course, first priority. This urgency accomplished to the utmost possible, ICHO authorities had to redefine the follow-up of restoration, considering that, due to its location in the epicentre of the earthquake zone, more than 70% of Arg-E-Bam had been ruined. Therefore, experts from UNESCO World Heritage Centre [whc.unesco.org], ICOMOS [www.icomos.org], its specialized documentation Committee ICOMOS/ISPRS, CIPA [cipa.icomos.org] and ICCROM [www.iccrom.org] joined to assess the state of damage and plan out rehabilitation, consolidation and reconstruction.

Requirements and technical solution

An initial step for any further procedure was defined in establishing a basic map to organise the consolidation of unstable structures as well as clearing the debris and ruins. Then, a precise as-built map of the site, more complex than a simple topographic line map or wall by wall cross sections should serve as a starting point for reconstruction tasks. In order to provide these maps, members of the companies Riegl LMS Austria and NPR Co Iran joined into a team to perform a surveying campaign on the devastated monument by means of a recently introduced technology. Using a hybrid sensor consisting of a 3D laser scanner and a calibrated digital camera, an innovative solution to optimise surveying tasks has been proposed. The basic idea lies in a combinatory instead of a counteractive approach, benefiting from both photogrammetry's and laserscanning's advantages: the most impressive result of laser scanning is the overall accuracy in the description of surfaces, whereas the strength of photogrammetry lies, between other features, in its capability of recognizing edges and details.
The project in Bam was intended to demonstrate the capacity of a system developed to exploit this complementary bi-technique, to subject it to a thorough examination in praxis and to check the product quality of the results as low-volume data acquired on specific objects of interest.
As the site of the Citadel Bam had been largely undocumented before the earthquake, the lack of general maps reinforced the difficulty of the working conditions and explains the workflow that had to be chosen in order to correspond to a request by ICHO.

Project description

The requested outputs included:

- traditional topographic maps of the remains
- cross sections and volumetric measurements
- vectorization of cracks and bricks
- traces of construction work and decay
- generation of simplified geometrical 3D models
- provision of easy-to-use view with measurement capabilities in global coordinates

Partly, these products could have been gained by performing traditional photogrammetric procedures. However, the multisensor use permits a much faster, more complete and therefore more efficient data acquisition, and extremely widespread possibilities in the final exploitation of the data.

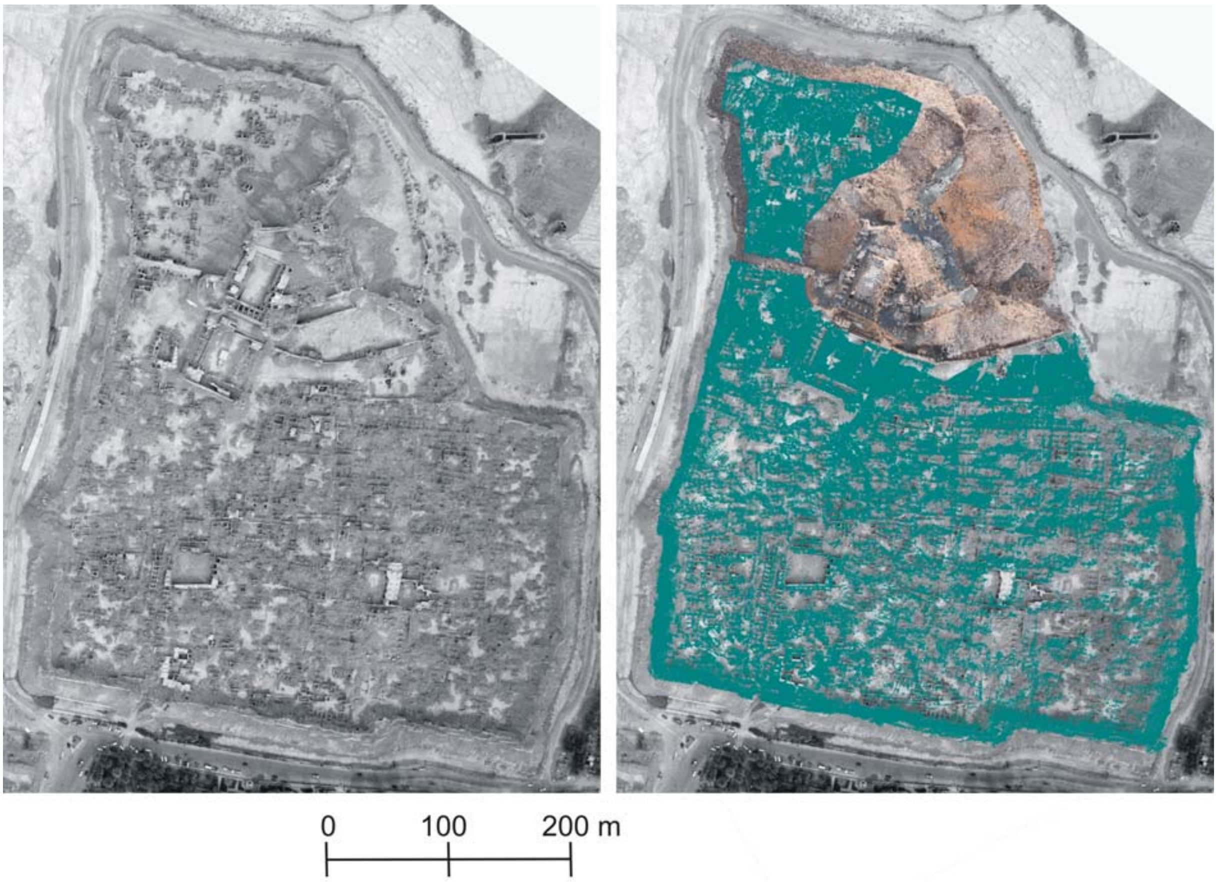

Fig.1 Left: Airborne photograph before the earthquake; Right: The superposed true-coloured point cloud of the area of main interest. The green coloured point cloud shows the area of secondary interest, captured as a by-product of the scanning campaign.

The subsequent instrumentation has been used:

- a high performance long-range laser scanner (RIEGL LMS Z420i) for acquiring geometric data
- (beam divergence 0.2mrad, operating range > 800m, single shot accuracy 10mm/5mm improved by scan sequences)
- about 80 cylindrical retro-reflective targets for scan-registration (reflector constant 25mm). As the coordinates of these are known – being surveyed through GPS – the project data is registered immediately in a global coordinates system
- a high resolution digital camera (Nikon D100, 6mio pixel; equipped with a 14 mm lens) mounted on top of the scanner providing the acquisition of calibrated photographs, consequently automatically registered. Camera and laser form a so-called hybrid sensor.
- An operating software package managing acquisition, registration and archiving tasks (RiSCAN PRO). A vectorization software (Phidias) and a software to generate triangulated models (Polyworks)

Project implementation

Data acquisitions have been carried out within four days in February 2004. The hybrid sensor (scanner and camera) and the data acquisition notebook have been operated by a single person. Corresponding to the field of view and range of the scanner, the required point density on the object's surface, the resolution of the camera and the disposable time, in total, 25 scan positions have been necessary to cover an area of approximately 200m x 200m: 24 adjacent ones around the ruler's place that had been considered as object of main interest, and one supplementary position from the opposite outer wall of Arg-E-Bam. Figure 2 shows a map of the scan positions from a bird's-eye view.

The crew split into three teams working in parallel: a scanning-team, a surveying-team, and a post processing team working in parallel. First, more than 80 reflectors were positioned onto strategically important points in and around the governing place. The more reflectors are used, the less problems occur during the online registration while scanning and the stability of the registration is increased. As these reflectors served as tie-points for merging the data of different scan positions. Their locations were chosen such as to guarantee visibility of 4 reflectors from each scan position. Ideally, as many reflectors as possible are surveyed by total station or GPS beforehand:

- allowing redundancy and independent control of the registration accuracy of each single scan.
- With the complete control point list in the computer, the automatic correspondence finding algorithm works faster and more reliable, because natural retro reflectors (e.g car lamps, licence plates etc.) are not used
- for special “island scans” no connection reflectors have to be measured by the scanner
- The measurement of the control points by e.g the total station is much faster than the registration of a single scan where not enough reflectors can be detected by the scanner due to difficult access for the reflector placement or poor visibility. With other words: the whole workflow from the scan to the post processed data is much faster and reliable.

By identifying a minimum of four known reflectors and saving new found reflectors in addition, the list of tie points in the coordinate system of the project – comprising all scan positions – was systematically extended. The description of these points, and consequently every measured point, in global UTM coordinates was made possible belatedly by the data of the dual frequency GPS receivers disclosed to the nearest known country GPS points for direct geo-referencing purposes. The results were imported as text-file in the scanner operating software RiSCAN PRO. All scan data was used for the hybrid multi station adjustment of RiSCAN PRO.
The single scans were merged immediately after data acquisition in order to check completion of the data set and to eliminate zones of scan shadow.

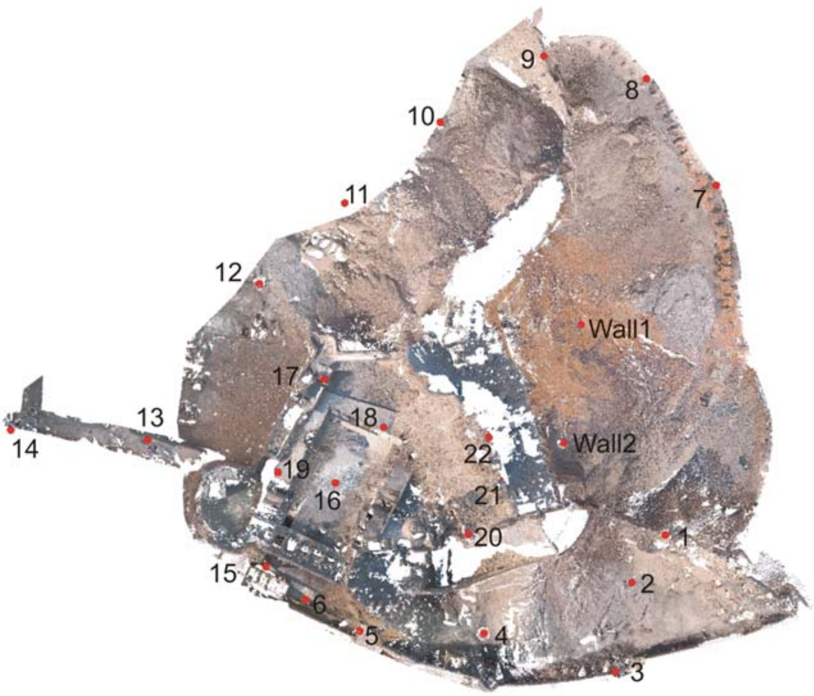

Fig. 2.: Red dots indicate the 25 scanner positions

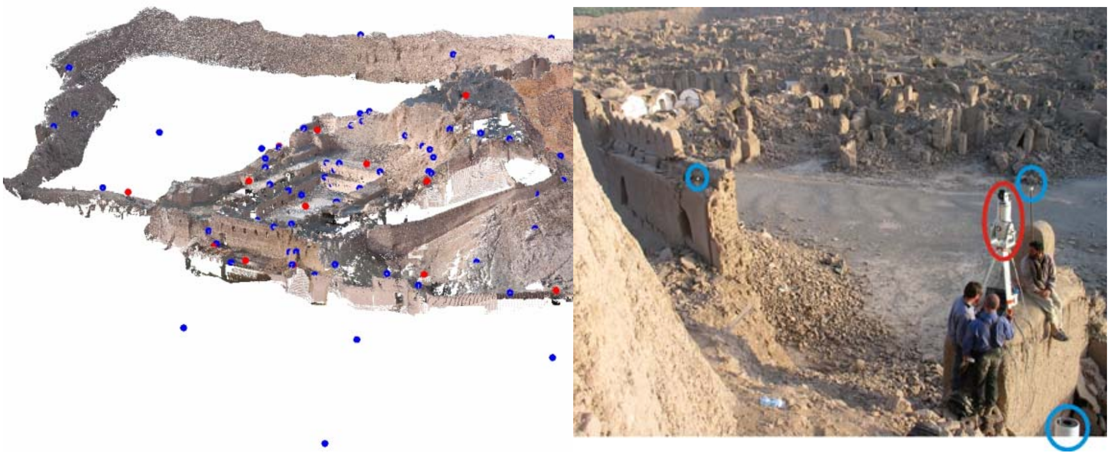

Fig 3: Left: Red dots indicate the scanner positions, blue ones the used tiepoints. Right: The hybrid sensor at work

Single scan position workflow

After executing a so-called panorama scan (predefined parameters: 2 million measurements, 4 minutes per scan) all reflecting targets within the field of view of 80deg x 360deg can be found and, by comparison with the pre-established project coordinate system, tiepoints are extracted. Both procedures are fully automated and the transformation matrix from the scanner's own coordinate system to the project coordinate system is calculated instantaneously. The reflectors are fine scanned to maximize the registration accuracy. The panorama scan is thus the ideal scanner setting for tiepoint detection. Now, additional detail scans or scan sequences can be performed, to increase the point density and resolution on details of interest. In a next step, the number of photos necessary to cover the corresponding horizontal field of view is calculated (e.g: 7, for a 360° field of view and the 14mm lens). The pictures were taken by the calibrated Nikon D100 camera, stably mounted on top of the scanner. Camera parameters are adapted to specific conditions of light (e.g. time of exposure), without effecting the calibration. The mathematical relation between the two sensors is defined by a hardware calibration (effectuated beforehand either by the manufacturer or by the operator himself). In addition to the internal camera calibration a mounting calibration guarantees a reliable correspondence of image and scan data. This mounting calibration can easily be checked and optimised by the user for each new mounting of the camera or a change of the lens.

The colouring of the scan data and the visualization of the reduced (resampled) scans takes not even a minute. After the optical control of the well registered and coloured data the scanner is packed in a robust carrying case and the equipment is carried to the next scan position. Usually, the instrument can be used more comfortably being installed on a mobile platform and commanded wireless. The harsh conditions in Bam made such impossible, thus slowing down the workflow and reducing the amount of possible scan positions. Thanks to helpful inhabitants of Bam City, carrying the equipment across the large and hard to access area was facilitated considerably.

After data acquisition: Checking data consistency and accuracy

After completion of data acquisition the online generated registration has been improved by the multi-station adjustment feature of RiSCANPRO. Registration accuracy has been analysed and the results are summarized in table 1. With a minimum of 5, a maximum of 32 and an average number of 16 reflectors for single scan registration, a satisfyingly high accuracy could be achieved. The reason of the rather high number of tiepoints for each scan is the automatic recognition and the deliberate redundancy. The additional work in the field allows a much better efficiency of the overall process of scanning and post processing.

	Average	Minimum	Maximum
Standard deviation before multi station adjustment	0.0042 m	0.0026 m	0.108 m
Standard deviation after the multi station adjustment	0.0038 m	0.0025 m	0.059 m

Table 1: Comparison between the registration accuracy of the laser scanner before and after multi station adjustment

Some tiepoints were surveyed by a total station. These surveyed points (control points) serve to registration into the global coordinate system and to minimize standard deviation.

To estimate the accuracy of applying the high resolution images to the geometrical data, the residual deviation of the reflector positions is determined. It derives from the scan data to the reflector centres measured from the image data. For this purpose – automatic extraction of the reflectors - the flash of the camera is employed.

Examples of data extraction from project data

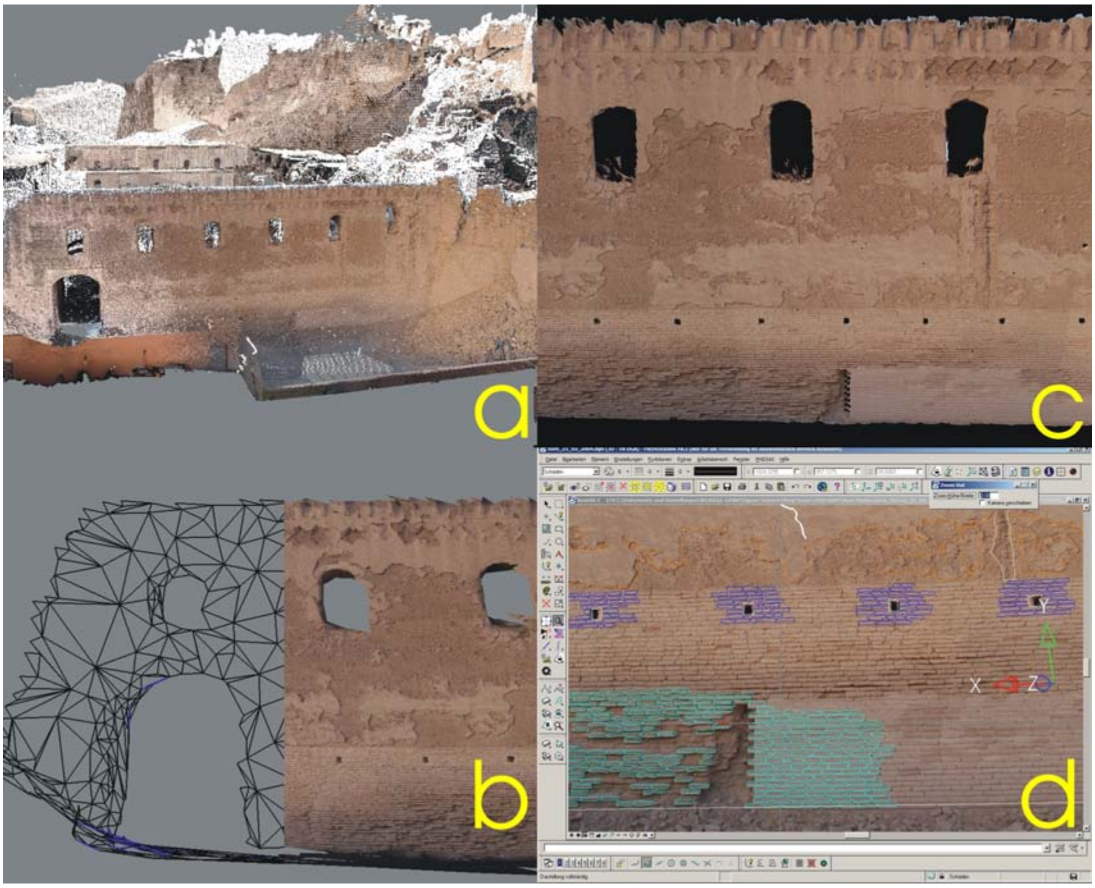

Fig 4: The primary results:
a: The colored point cloud: Lightweight 3D visualization of the complete project data set
b: The decimated mesh with high resolution texture: data reduction maintaining geometrical information
c: The true orthophoto
d: 3D Monoplotting: Instant access to the raw data, CAD processing of point clouds and orientated photographs

The four images demonstrate interim results as a provisional step between raw data and the desired final product. Thanks to an immediate access to the full information, preparatory editing can take place in the field or right after data acquisition. This is especially recommended for the generation of a coloured point cloud as shown in Figure 4 (picture a) for reasons of data control. By visualizing the whole data set (resampled) of already performed scans, the operator can easily decide upon eventually necessary further scan positions to close gaps. A photographic colour value is assigned to each scan point, the resolution of the lightweight model is that of the resampled scan. Picture 4b illustrates the mesh onto which the full high-resolution of the photographic information can be applied. The requisite steps for decimating, meshing and texturing a single scan can be undertaken in the operating software RiSCAN PRO. The same for the production of ZOP – orthophotos containing depth information (the “z-value”) as 2,5 interpretation of the data (picture 4c). Picture 4d shows a 3D monoplotting digitization technique in a screenshot of the post processing software, vectorizing bricks of the same wall. PHIDIAS is a program application for MicroStation CAD environment. The basis of a combined evaluation of point cloud and images is the perspective representation of the complete data. Both point cloud and oriented images are taken over without friction losses and the evaluation can start without any additional adaptation. Hence the post processing of complex 3D scan- and image data can be performed in the broadly known CAD environment, profiting from a set of CAD tools and specialized facilities to define planes and free-form surfaces. After importing of the project data, the oriented images are at the post processor’s disposal: in a 2D working space the projection and extraction of features for 2D maps or 3D vectorization can be performed directly in 3D orientation.

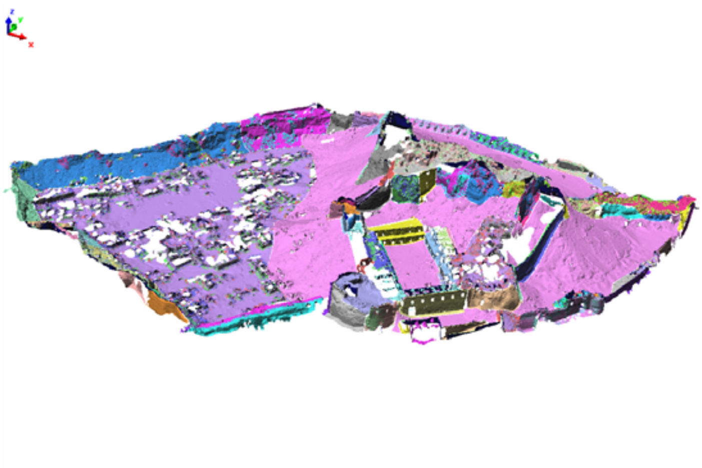

Fig 5 All 25 scans merged into one single mesh by means of professional mesh processing software, e.g. Polyworks.

Figure 5 shows the total of 25 scan positions. An octree filter has been applied on the huge amount of scan data (around 2 mio measurement points per scan position), preserving only one single representative point per 10 cm cube. Then, the pointcloud has been segmented in Polyworks according to the alignment of the triangulation, assigning a corresponding colour. This way, the result shows less gaps then in a fully-automated process, thanks to a more regular distribution of the points in the planes.

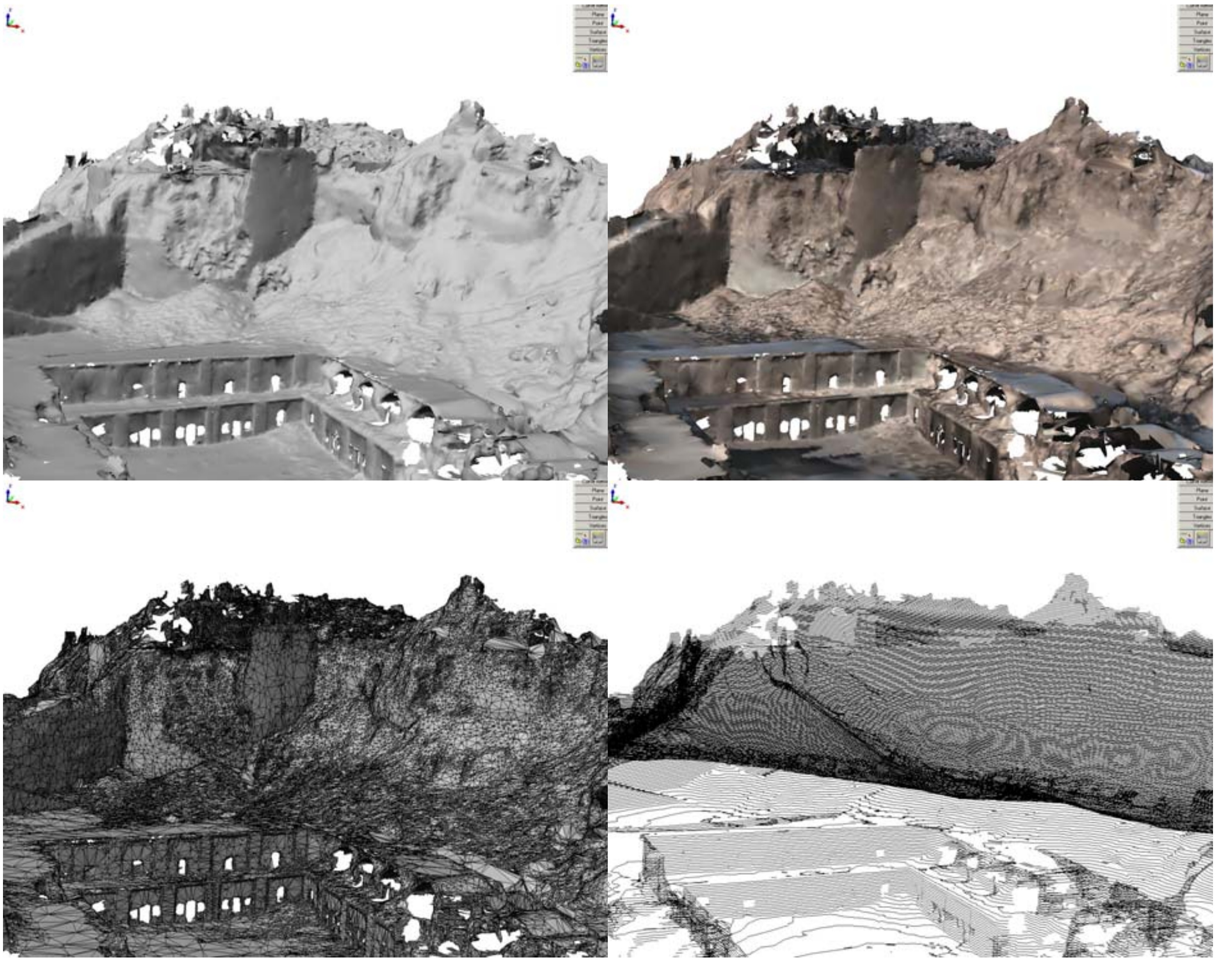

Fig 6: All 25 scans merged into one single mesh
picture 1: left above: smoothed suface without texture
picture 2: right above: smoothed surface with color per vertex
picture 3: left below: combined representation of triangulation and the solid mesh surface
picture 4: right below: Computed Isolines of the model

Based upon the primary results as shown in Figure 4 the following data post processing results were gained: The four pictures in Figure 6 represent the same data in different visualization modes. To generate this polygonal model, the registered and 10cm-resampled RiSCAN PRO raw data of all 25 scan positions were calculated by Polyworks software (duration: 3 hours) to one single mesh. This mesh has been smoothed (picture 1), then coloured (picture 2). As Polyworks is not designed to read calibrated photographs, the mesh is coloured per vertex, then re-imported in RiSCAN PRO for mapping the high resolution texture.
In picture 3 the edges of each triangle of the mesh are extrapolated.
Finally, picture 4 displays polylines, ready for further processing in any CAD software. It is rather impossible to load directly high resolution meshes into CAD software. The surface model is considered as adequate result to generate macro-maps of isolines and cross-sections. For details, a vectorized analysis of limited areas of special interest is possible.

Fig.7: Volume calculation, the shown segment, e.g., consists of 137.659 m³ bricks and debris

Figure 7 demonstrates an example for a polygonal model of a part of the citadel, five single scans were merged and prepared for volumetric calculations. Therefore, the model has to be watertight, remaining wholes have to be filled. Due to the lack of a general topographic map, the ground level had to be estimated.

Conclusion

The versatile hybrid instrument corresponds ideally to architectural, topographic and archaeological requirements. The high speed of operation allows a quick data acquisition, and it is therefore possible to build up an archive of historical sites and monuments for multipurpose post-processing, aiming at satisfying demands of detailed feature extraction on ancient walls or to facilitate the exact modeling of roughness and texture for material studies needed by archaeologists and to meet typically afforded documentation standards not only under such tragic circumstances like the catastrophic earth-quake in Bam.

Acknowledgements

Arg-E-Bam can not only be considered as a former main economic factor but also as the symbol for the vitality of the region of Bam, and a means of identification for the inhabitants. Therefore, the authors hope for a quick and efficient reconstruction and would like to thank ICHO experts and authorities who initiated and supported the project, as well as Rayan Naghsheh Co. who provided the GPS and surveying team, furthermore Mr. M. Noor Allah Doost who managed the surveyors, and all those hard working and impressively motivated helpers from Bam who assisted the practical implementation.