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3D mosaic documentation using close range photogrammetry

M. Lo Brutto[1], A. Garraffa[1], L. Pellegrino[2], B. Di Natale[3]

[1] *DICAM - University of Palermo, viale delle Scienze, Palermo, Italy,*
(mauro.lobrutto, alessandra.garraffa)@unipa.it
[2] *CRPR – Ass. Regionale BB.CC. e Identità Siciliana, Via dell'Arsenale 52, Palermo, Italy*
pelegelino@gmail.com
[3] *M.Sc. in Preservation and Restoration of Cultural Heritage - University of Palermo*
barbara.dinatale@yahoo.it

***Abstract* – The paper describes the close range photogrammetric survey of a roman mosaic stored at Regional Archaeological Museum “Antonino Salinas” in Palermo (Italy). The aim of the work is the production of a full-scale representation (scale 1:1) of the mosaic useful for documentation and restoration processes. The research has allowed evaluating limit and potentiality of image-based approach using photogrammetric and computer vision (Structure for Motion) techniques in a context where the metric point of view is a very important factor.**

I. INTRODUCTION

The 3D survey of archaeological cultural heritage is a fundamental step for the knowledge and the study of archaeological finds and sites. Many information can be obtained by a correct 3D documentation: measurements about the shape and the size of the objects, information about the state of preservation, data related to material deterioration, etc..

The techniques available in 3D survey of cultural archaeological heritage allow obtaining very accurate and detailed metric data for both great and small dimensions objects. In particular, in archaeology the 3D survey of objects that required a very high accuracy (<1 mm) can be carried out typically with active sensors (like triangulation-based range sensors and pattern projection sensors) or passive sensors (like image-based techniques) [1]. In the last years, image-based techniques have become increasingly used for 3D survey thanks to the integration of photogrammetry and computer vision. This integration has enabled the development of fully automated pipeline; furthermore, it has allowed to get performance comparable with those of the active range sensors as demonstrated in several recent studies [2,3]. In archeology this approach is also becoming more and more popular mainly due to the availability of much low-cost and open-source software, to the easiness of the processing steps and to the low budget required for the devices.

As it is widely known one of the main objective of photogrammetry is measurement accuracy. For this reason, the use of close-range photogrammetry in metrology applications is not new. The term “vision metrology” is also often used to describe this technology when it is applied to higher accuracy 3D measurement tasks [4]. Applications are typically carried out in engineering and manufacturing scenarios where it is necessary to have measuring accuracy in the range of a few tens of micrometers to tenths of a millimeter and where object size is in the range 1-10 m [5].

Computer vision, instead, aims at the automatic image orientation of large unordered and un-calibrated image sequence using Structure for Motion (SfM) algorithm [6] and does not put any emphasis on measurement accuracy.

Photogrammetry and computer vision allow to produce final products with comparable feature but originally computer vision, and in particular the SfM approach, was not considered sufficient suitable for metrology applications due to the lack of results in term of accuracy and reliability of the process. Now some advances have been done in SfM software (in particular in commercial software like Agisoft Photoscan and Pix4D) that allows using the SfM pipeline also in metrological context. However, many aspects (like camera network or camera calibration) must be taken into account.

In archaeological cultural heritage there are some circumstances in which the metrological aspect is very important; for example the documentation of ancient mosaics requires sub-millimeter precision for an appropriate planning of restoration and conservation activities. The *tesserae* of the ancient mosaics are unique elements characterized by high geometric and material complexity. The traditional survey approach includes the representation of single *tesserae* using a transparent polyester film which is resting “in contact” with the mosaic; all the *tesserae* are drawn on the film in order to obtain a full size drawing (scale 1:1). This work allows to study and to document with a high level of detail the techniques used for the mosaic, any discontinuities due to previous interventions and the presence of damaged areas. This type of documentation, although extremely detailed and accurate, has several drawbacks: the long time required for a precise representation, the difficulty of operating in situ, the operator subjectivity. In addition, the drawing is quite complex to use and to reproduce and not easily to carry due to its size.

The use of image-based techniques is a great support for the survey of mosaics, in particular for the documentation of the single *tesserae* and for a full size representation (scale 1:1). Some applications have been done in recent years as the close-range photogrammetry survey of the mosaic of Saint Mark's Basilica in Venice [7]. In this work, the authors have obtained an ortho-image and a 3D model of the entire mosaic of the Basilica (2100 m²) in scale 1:1 using a traditional photogrammetric approach. More recently, some tests has been done to compare different mosaic point clouds from laser scanners and from SfM, for the documentation of three ancient roman mosaics, and to evaluate the best point cloud resolution for the detailed shape analysis of each *tessera* [8].

In this paper the results of the 3D close range photogrammetric survey of an ancient roman mosaic preserved in the Regional Archaeological Museum "Antonino Salinas" in Palermo (Italy) were described. The main purpose of the research is to obtain an ortho-image and a 3D model with a very high level of accuracy and details that could be used as support for restoration and preservation processes. The mosaic was surveyed using a high resolution digital camera and close range photogrammetric/SfM approach. The work has allowed evaluating the limit and the potentiality of the integration of photogrammetric and SfM methods as regards the camera calibration step and the potential accuracy in a metrological context.

II. THE ROMAN MOSAIC

The roman mosaic belongs to the archaeological site of “Piazza della Vittoria” which is located within the historic center of Palermo (Sicily, southern Italy). The discovery of this archaeological site in one of the oldest and most central part of Palermo has revealed two buildings, called "Building A" and "Building B". The construction of the “Building B” is dated to the late second century B.C. and it dates back to the Hellenistic period; the “Building A” is instead dated to the early third century A.D. and it dates back during the Roman imperial age [9]. The remains visible today of “Building A” are composed of parts of the walls and of decorations unearthed during various excavations and archaeological surveys. “Building A” is characterized by rich mosaic pavements that were partly removed and preserved in the Regional Archaeological Museum "Antonino Salinas" in Palermo and in part were left *in situ*.

The studied object is a bichrome *opus tessellatum* mosaic with geometric decorations (Figure 1). The mosaic is made of square *tesserae* of black and white marble. A careful analysis of the *tesserae* shows the use of different types of marble due to previous work of restoration. Several black *tesserae* are different from original and in some areas the white *tesserae* were replaced with yellow *tesserae* that clearly show areas of previous restoration works (Figure 2).

Fig. 1. The bichrome opus tessellatum mosaic.

Fig. 2. Area of previous restoration.

The mosaic decoration is constituted by a geometric drawing obtained by the arrangement of the black *tesserae* on the white background. The black *tesserae* are arranged to form rows of tangent recumbent spindles-shaped which constitute a grid with squares with sides of about 40 centimeters [10]; each square have a crosslet with chevrons in the center. The perimeter of the decoration is constituted by a double row of black *tesserae* and by a broad frame of white *tesserae*.

The roman mosaic is not in a good state of preservation; the entire surface is concealed by a thick layer of coherent deposit, referable to previous restoration works, which does not allow a correct interpretation of the mosaic. During the detachment phase from the original site and the subsequent relocation inside the museum, in some areas it was not observed the original trend of the *tesserae* compromising the geometric drawing and creating decorative shapes not suited to the decorative fabric. The mosaic is also not perfectly flat and has several depressions due to a clumsy transfer from the origin site.

III. DATA ACQUISITION

The mosaic is located in one of the rooms of the Regional Archaeological Museum “Antonino Salinas” in Palermo (Italy) currently not open to the public; the mosaic have a rectangular shape with dimensions of about 5.50 m per 4.20 m. The logistic conditions have not presented particular problems for the photogrammetric survey; to get the best lighting conditions the photogrammetric survey was performed without the use of artificial lights or spotlights but only using natural light.

The images acquisition was carried out using a Nikon D5200 digital camera equipped with a 28 mm Nikkor AF-S f/2.8G fixed focus lens; the camera has a CCD sensor with size of 23.5 mm × 15.7 mm, a pixel size of 3.9 μm and an effective resolution of 6000 pixels × 4000 pixels. The camera-to-object distance was chosen equal to 1.5 m; the image scale was 1/54 and the coverage of each image was about 1.2 m × 0.8 m. Because the camera focal length was 28 mm, each pixel was about to 0.2 mm in the object space (Table 1). This value can be considered acceptable for the final result.

Table 1. Survey parameters.

Camera	Nikon D5200
Focal length	28 mm
Camera-object distance	1.5 m
GSD	0.21 mm
Image coverage	1.2m x 0.8m
End lap and side lap	70%
Number of images	401

During the images acquisition the focal lens was set to manual focus after adjusting it to the average camera-to-object distance of the project and then adequately fixed throughout the shooting process.

The images were taken with the camera mounted on a tripod (Figure 3); this condition has allowed to acquire nadiral images maintained the sensor position parallel to mosaic’s plane.

A nadiral stereoscopic coverage was planned for the whole mosaic with strips parallel to the longer side of the mosaic. The photogrammetric strips were selected providing an end lap and a side lap of 70% (Figure 4) .

Some additional convergent strips were also planned along the edge of the mosaic to increase the redundancy of the measures at the edges of the photogrammetric block and to limit bowl-effect in the 3D model. A total of 401 images, divided into 17 nadiral strips and 4 convergent strips, were obtained (Figure 5).

Fig. 3. Photogrammetric survey.

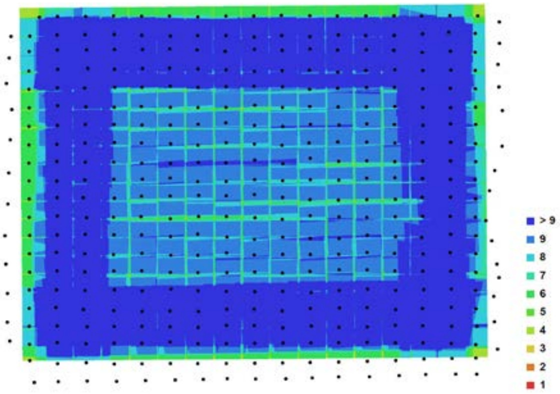

Fig. 4. Camera location and image overlap.

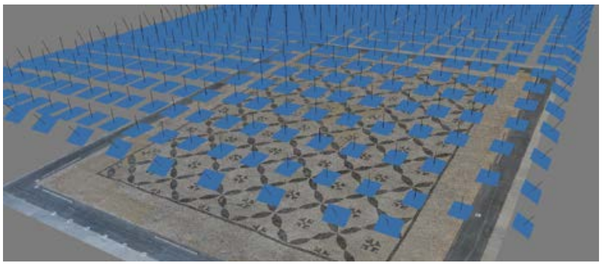

Fig. 5. Photogrammetric coverage of the mosaic.

To evaluate the theoretical precision of the survey the traditional photogrammetric formulas for so called ‘normal case of stereo-photogrammetry’ were used [11]. The theoretical precision σ_X and σ_Y, respectively in X and Y coordinates, was calculated from:

$$\sigma_X = \sigma_Y = \frac{D}{c}\sigma_{X'} \qquad (1)$$

where D is the camera-to-object distance, c is the focal length and $\sigma_{x'}$ is the image measurement precision. The theoretical precision σ_Z along the Z direction depends also on the ratio D/B where B (baseline) is the distance between the two camera stations and was calculated from:

$$\sigma_Z = \frac{D^2}{c\cdot B}\sigma_{px'} \quad (2)$$

where $\sigma_{px'}$ is the image measurement precision of the x-parallax.

These formulas give reasonable approximation of achievable precision and depend primarily on image measurement precision. For a close range photogrammetric/SfM approach the image measurement precision depend on the accuracy of feature extraction and feature matching, that generally can achieved a sub-pixel accuracy [12]. For our study it was supposed $\sigma_{px'}=\sigma_{x'}$ and an image measurement precision of 0.5 pixel, corresponding to 1.95 µm; the theoretical precision was estimated at 0.10 mm for X and Y and 0.42 mm for the Z direction. The precision of 3D point measurement can be calculated as

$$\sigma_{XYZ} = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2} \quad (3)$$

It was equal to 0.44 mm. These value, and in particular the X and Y accuracy, are compatible with the accuracy of photogrammetric measurements required for the production of an ortho-image at full-scale representation (scale 1:1).

Some 12 bit coded targets were positioned around the mosaic to define a local coordinate system and to correctly link next close range photogrammetric projects for monitoring purpose. Moreover, eleven calibrated bars were placed along the edge of the mosaic; calibrated bars are of aluminum and are long 50 cm (Figure 6).

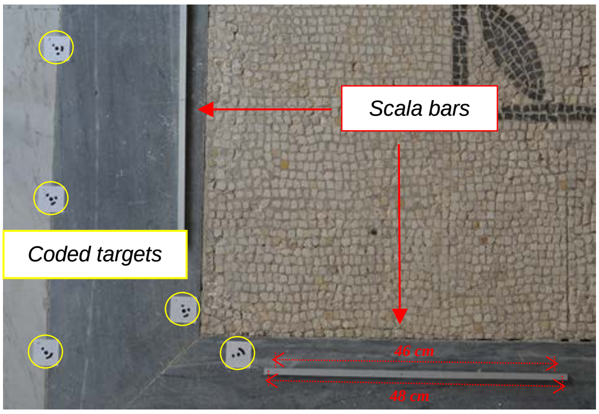

Fig. 6. Coded targets and scale bars.

Every bar has two calibrated distances; one of 48 cm and another of 46 cm. The measurement of the distances was done with a computer numerical control machine with an accuracy of ±50 microns. For each bar one distance was used to scale the photogrammetric model, the other to check the accuracy of the photogrammetric survey.

IV. DATA PROCESSING AND RESULTS

The images processing was done through the typical SfM workflow using the well-known commercial package PhotoScan Professional Edition v.1.1.

The software provides a sequence of automatic steps for image orientation and image matching; moreover, PhotoScan allows extracting 3D models and ortho-images with a very high level of detail. During image orientation (called “photo alignment” in PhotoScan) the software estimates both internal camera parameters and external camera orientation for each image. PhotoScan is the typical SfM software that has also integrated photogrammetric procedures; in fact, in the latest versions it is possible to recalculate the orientation parameters through a bundle block adjustment with self-calibration (called “optimization” in PhotoScan), to use coded targets for points detection and known distances as metric constrains, to obtain some parameters about the precision of the process and to assign an accuracy value to the metric constrains (ground control points or distances).

The data processing step was also used to test some different camera calibration approach in photogrammetric/SfM pipeline. In particular, two main approaches were evaluated: in the first the self-calibration of the PhotoScan “optimization” process was used, in the second a standard camera calibration process using the photogrammetric software PhotoModeler, convergent camera network and a set of coded targets was carried out (Figure 7).

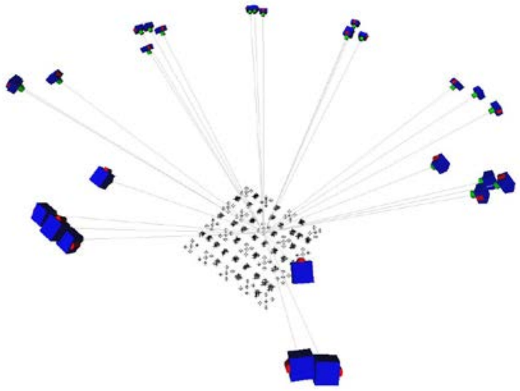

Fig. 7. PhotoModeler camera calibration network.

The parameters calculated with PhotoModeler were then imported and used for PhotoScan processing. For each test we have also calculated two different datasets of parameters: one with all the internal camera parameters (principal distance, principal point position, skew, radial and tangential distortion coefficients) and another with only principal distance, principal point position and radial distortion coefficients. This choice was done to evaluate if skew and tangential distortion coefficients, that are generally less important for the camera calibration, can significantly affect in our surveying condition the accuracy of the photogrammetric block.

The camera calibration parameters calculated with PhotoModeler were converted in PhotoScan format using the Agisoft Lens package for the dataset with all the internal camera parameters and a MATLAB routine, developed by the 3DOM unit of Bruno Kessler Foundation (FBK) of Trento (Italy), for the dataset with only principal distance, principal point position and radial distortion coefficients. This step is necessary because PhotoModeler uses the typical photogrammetric formulation of camera calibration parameters, while PhotoScan uses for the same parameters, the computer vision formulation.

Four different PhotoScan projects were done performing the camera orientation using a maximum of 40000 feature points for image; all the projects were calculated in an arbitrary reference system by applying a free-network solution bundle block adjustment and by using only the 48 cm calibrated distances of the eleven bars to scale the photogrammetric model. The 46 cm calibrated distances of the eleven bars were instead used as check control distances to evaluate the accuracy of the projects. This procedure was chosen in agreement with a German standard (VDI7VDE 2634 Part 1) [13] for evaluation of object-space accuracy of 3D point measurement systems based on the length measurement error (LME). This value is the difference between the distance calculated from the photogrammetric process and the calibrated distance of the bar; the root mean square (RMS) value of all the differences provides an assessment of the precision/accuracy of the photogrammetric measurement and can be compared with the theoretical 3D precision.

The result of the calibrated distances RMS for the four PhotoScan projects can be showed in table 2.

Table 2. Statistical results of the camera orientation.

	RMS scale distances ***[48 cm]***	***RMS check distances*** ***[46 cm]***
PS self-calibration *all parameters*	*0.033 mm*	*0.049 mm*
PS self-calibration $c_x, c_y, x_p, y_p, K_1, K_2, K_3$	*0.051 mm*	*0.071 mm*
PS with PM self-calibration *all parameters*	*0.288 mm*	*0.290 mm*
PS with PM self-calibration $c_x, c_y, x_p, y_p, K_1, K_2, K_3$	*0.145 mm*	*0.150 mm*

PS = PhotoScan; PM = PhotoModeler Scanner
c_x,c_y *= focal length;* x_p,y_p, *= principal point coordinates;*
K_1,K_2,K_3 *= radial distortion coefficients*

As can be noted from table 2, the accuracy obtained in all tests are always better than the theoretical precision; this seems to highlight the inadequacy of traditional photogrammetric formulas to correctly estimate the accuracy of the survey in a close range photogrammetry/SfM approach. The PhotoScan self-calibration allows to obtain much better accuracy than using the parameters calculated with ad hoc calibration. In particular, estimating all the internal camera parameters (principal distance, principal point position, skew, radial and tangential distortion coefficients) it is possible to achieve a very high level of accuracy typical of metrological context.

A more accurate analysis with regard to calibration parameters shows that the large differences between PhotoScan self-calibration projects and PhotoScan projects with PhotoModeler self-calibration parameters are probably due to the variation in principal point coordinates (Table 3).

Table 3. Camera calibration parameters.

	PS self-calibration	***PM self-calibration***	***Differences***
c_x	*7434.48 [pix]*	*7436.91 [pix]*	*-2.43 [pix]*
c_y	*7435.17 [pix]*	*7437.51 [pix]*	*-2.34 [pix]*
x_p,	*3015.74 [pix]*	*3015.89 [pix]*	*-0.15 [pix]*
y_p,	*2006.82 [pix]*	*1984.92 [pix]*	*21.9 [pix]*
Skew	*0.17*	*0.00*	*0.17*
K_1	*-9.76E-02*	*-1.01E-01*	*3.36E-03*
K_2	*1.82E-01*	*2.09E-01*	*-2.68E-02*
K_3	*-1.93E-01*	*-3.06E-01*	*1.13E-01*
P_1	*-1.83E-05*	*-2.59E-04*	*-2.86E-05*
P_2	*1.07E-04*	*1.36E-04*	*0.00E+00*

PS = PhotoScan; PM = PhotoModeler Scanner
c_x,c_y *= focal length;* x_p,y_p, *= principal point coordinates;*
K_1,K_2,K_3 *= radial distortion coeff.,* P_1,P_2 *= tangential distortion coeff.*

The principal point position seems to be the most sensitive interior orientation parameter, since differences in c_x and c_y coordinates control the image coordinate uncertainty [14]. Our results are however slightly differ from [14] because the PhotoScan self-calibration give better solutions than high precision self-calibration with convergent image-network configuration; this issue requires more detailed analysis and further tests.

The PhotoScan project that had the best accuracy (*PS self-calibration all parameters*) was used to obtain a detailed point cloud a Digital Surface Model (DSM) with a resolution of 0.8 mm was also calculated.

An ortho-image with a resolution of 0.5 mm was finally produced (Figure 8). The ortho-image obtained in this work contains all metrics information of a traditional mosaic survey. It permits to examine the numerous form of irregularities, the size and position of the *tesserae* and the presence of erosion and patina deterioration with non-invasive and more fast procedures.

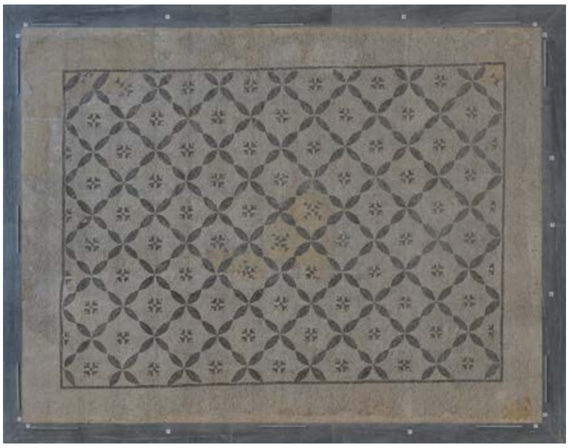

Fig. 8. Ortho-image of the mosaic.

V. CONCLUSIONS

The photogrammetric survey has allowed obtaining an ortho-image of a roman mosaic, compatible for a full scale representation (scale 1:1), that has all metric information of a traditional mosaic survey and permits to draw the *tesserae* layout in a very accurate way.

This type of documentation can be repeated in time in such a manner to allow monitoring and analyzing the mosaic even after restoration processes and changes of the surface. Furthermore, the photogrammetric/SfM approach, thanks to the high level of detail, allows, during the restoration phase, to overcome the realization of plaster casts for the replacement of missing or damaged *tesserae*.

The high accuracy obtained with a photogrammetric/SfM approach shows that these techniques could be applied in metrological context for archeological 3D documentation. The accuracy evaluation shows also that the camera calibration is still an open issue because the typical photogrammetric scheme could not always be suitable for this approach.

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