# 3D mosaics survey: analysis of photogrammetric/computer vision approach in a metrological context

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***Abstract*** **– The goal of the paper is evaluate photogrammetric/computer vision approach in a metrological context for 3D mosaics survey. The aim of the mosaics survey is the production of a full-scale representation (scale 1:1) useful for the documentation and for the restoration processes.**
**In order to evaluate the optimal photogrammetric/computer vision workflow in this work three different surveys have been done for three mosaics with different size and location. Two of these are stored at Regional Archaeological Museum "Antonino Salinas" in Palermo (Italy) and the other one is stored at Regional Archaeological Museum "Baglio Anselmi" in Marsala (Italy). The research has allowed to show the potentiality and the issues of photogrammetric/computer vision approach for the 3D mosaic documentation.**

## I. INTRODUCTION

Measurement and 3D modeling are important steps for the documentation and preservation of cultural heritage. Many researches and many experiences have been done in the last years using the more innovative and efficient survey techniques [1].

For certain types of cultural heritage such as paintings, frescoes and mosaics, the approach for the measurement and 3D modeling is very important because environmental factors and poor preservation conditions could affect the status and the integrity of the artworks or archaeological finds. These objects shall be monitored with very accurate metric measurements because small geometric variations could cause very serious damages.

Among the objects that require very accurate measurements (accuracy less than a millimeter) the mosaics represent a special case both for the variability of the size (the mosaics can be from a few decimetres to several meters) and for the different conditions of conservations (the mosaics can be in original site or preserved in a museum). Moreover, the presence of the *tesserae,* that can be consider the reference unit of these objects, make the mosaics survey not simple; although the dimensions of the mosaics could be in meters, the single *tessera* is always very small (generally few millimeters).

The creation of 2D products at full-scale representation (scale 1:1) is a requirement for the documentation and preservation all the details of these objects. Therefore, in terms of accuracy of the survey, the allowable errors should be of one or two tenths of a millimeter. These accuracies, typical of a metrological context, have generally been obtained in cultural heritage survey by laser triangulation 3D scanner, structured-light 3D scanner or photogrammetry. In literature there are not many example about these experiences; some interesting application can be find for paintings survey [2] or for mosaics survey [3].

In the last years, the integration of photogrammetric and computer vision techniques has been possible to realize more and more accurate products, both in metric and qualitative terms, only using image based approach without laser scanner [4].

The proposed work takes up and integrates an initial study presented at the 1st International Conference on Metrology for Archaeology about 3D survey of an ancient mosaic [5]. The aim of the work is to define a workflow for mosaic's survey using photogrammetric and computer vision techniques. In particular, the aspect that has been analysed and studied in detail is the accuracy assessment as regards the camera network chosen for the survey and the different camera calibration processes.

The work was carried out with three different datasets: two mosaics preserved in the Regional Archaeological Museum "Antonino Salinas" in Palermo (Italy) and another mosaic preserved in the Regional Archaeological Museum "Baglio Anselmi" in Marsala (Italy). The first and second belong to the "Piazza della Vittoria" archaeological site, located in the historic center of Palermo (Italy), and are dated to the early third century AD. The first mosaic (Fig. 1), already used in the previous study [5], is in two colours with geometric designs and size of about 5.50 m to 4.20 m; the mosaic is placed on the floor. The second mosaic (Fig. 2), known as the "carpet", is a geometric polychrome mosaic with a size of about 2.30 m to 1.75 m and is hanged on the wall.

The third mosaic (Fig. 3), originally placed in the compartment n. 36 of a domus of the first insula city of archaeological site of Lilybaeum, presents a geometric polychrome decorative motif. It is a very refined mosaic, characterized by different colours and a great attention to detail. This mosaic has a size of 4.50 m to 5.50 m and is placed on the floor.

*Fig. 1. First mosaic (Regional Archaeological Museum "Antonino Salinas" in Palermo - Italy)*

*Fig. 2. Second mosaic (Regional Archaeological Museum "Antonino Salinas" in Palermo - Italy)*

*Fig. 3. Third mosaic (Regional Archaeological Museum "Baglio Anselmi" in Marsala - Italy)*

## II. DATA ACQUISITION

In order to deepen the study about the photogrammetric/computer vision approach the same conditions of the first survey have been used for the new surveys (same camera, same camera network, same camera-to-object distance, etc.) [5].

The images acquisition was carried out using a Nikon D5200 digital camera equipped with a 28 mm AF-S Nikkor f/2.8 G fixed focus lens; the camera has a CCD sensor with size of 23.5 mm x 15.7 mm, a pixel size of 3.9 µm and an effective resolution of 6000 pixels x 4000 pixels.

A nadiral stereoscopic coverage was planned for all mosaics with strips parallel to the longer side of these. The photogrammetric strips have an end lap and side lap of 70%. The camera-to-object distance is 1.5 m; the image scale is 1/54 and the coverage of each image is about 1.2 m x 0.8 m. Given that the camera focal length is of 28 mm, each pixel is about to 0.2 mm in the object space. 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.

In this way three photogrammetric blocks were obtained, called Mosaic-1 for the first mosaic, Mosaic-2 for the second and Mosaic-3 for the third. Mosaic-1 and Mosaic-3 have almost the same number of images; Mosaic-2 is smaller and has about a quarter of images than the others (Tab. 1)

*Table 1. Photogrammetric blocks.*

| ***Datasets*** | ***Images*** | ***Nadiral Strips*** | ***Convergent Strips*** |
|---|---|---|---|
| *Mosaic-1* | 401 | 17 | 4 |
| *Mosaic-2* | 100 | 8 | 4 |
| *Mosaic-3* | 433 | 17 | 4 |

In order to have reliable metric products in the survey for all datasets some 12 bit coded targets and some scale bars were distributed uniformly around the mosaic (Fig. 4).

*Fig. 4. Example of coded target (in red) and scale bar (in blue).*

The 12 bit coded targets were used to define a local coordinate system, to improve photo orientation step and to correctly link next photogrammetric surveys of the mosaics. The scale bars were placed along the edge of the mosaic and used to scale the photogrammetric blocks and to check the accuracy of the 3D model (Tab. 2). Every scale bar is long 50 cm and has two calibrated distances; one of 48 cm (constraint in the tests) and the other of 46 cm (check in the tests). The measurement of the calibrated distances was done with a computer numerical control machine with an accuracy of ±50 microns. This value was used as scale bars accuracy during the orientation step.

*Table 2. Number of targets and scale bars used for every block.*

| | **Mosaic-1** | **Mosaic-2** | **Mosaic-3** |
|---|---|---|---|
| *Coded targets* | 30 | 22 | 25 |
| *Scale bars* | 11 | 11 | 10 |

## III. DATA PROCESSING

Data processing was carried out using photogrammetric and photogrammetric/computer vision software to evaluate the camera calibration process and the accuracy of the surveys.

### A. Camera calibration

The calibration process is one of the most important aspect of the photogrammetric workflow. The correct estimation of camera interior orientation parameters and lens distortion parameters is necessary in order to obtain accurate photogrammetric measurements. This aspect becomes even more important when the accuracy of the photogrammetric survey is less than one millimeter [6].

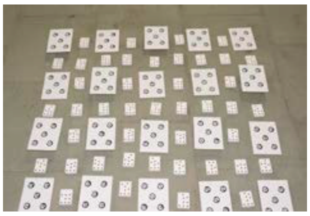
The camera calibration is generally divided into two steps. First the operator takes some pictures to a test field, generally done with coded targets; then the camera interior orientation parameters and the lens distortion parameters were calculate with a self-calibrating bundle adjustment, where interior orientation parameters and distortion parameters are unknown [7]. In some cases, camera interior orientation parameters and lens distortion parameters are calculated with the images of the photogrammetric survey. This process, called self-calibration, in photogrammetry generally involves a lower reliability of the unknown parameters due mainly to the poor reliability of the camera network.

In the computer vision, and especially in the Structure from Motion (SfM) approach, the camera calibration process is not considered a particularly important task and the camera parameters are almost always calculated with images of the survey and simultaneously to the calculation of the external orientation parameters of the photogrammetric block (self-calibration). The computer vision approach has been developed mainly with the aim to achieve maximum automation of processes and not the best accuracy like in photogrammetry. Therefore, the camera calibration issues have always been poorly considered.

In the survey of the mosaics the calibration phase assumes considerable importance for the high accuracy required for the correct 3D modeling and representation of the single *tesserae*.

For this reason several calibration methods have been tested to determine the most suitable workflow for this phase. The software used for the tests are a typical photogrammetric software for close range photogrammetry, *PhotoModeler Scanner* (PM) from EOS Systems, and one of the most popular and well-known photogrammetry/computer vision software *PhotoScan Pro* (PS) from Agisoft.

The camera calibration was performed using the respective coded targets of PM and PS (Fig. 5). The photos were taken in accordance with the classic rules for camera calibration in photogrammetry (multi-station convergent imaging network, images rotated by ±90°, etc.,) [7] obtaining two different calibration dataset: one for PM and one for PS (pre-calibration). Moreover, a further camera calibration was carried out using the typical SfM approach with PS calculating the camera parameters during the images orientation of the photogrammetric survey (self-calibration) (Fig 6). A total of three different sets of calibration parameters were calculated for each mosaic.



*(a)* *(b)*

*Fig. 5. Camera calibration test field for PM (a) and PS (b)*

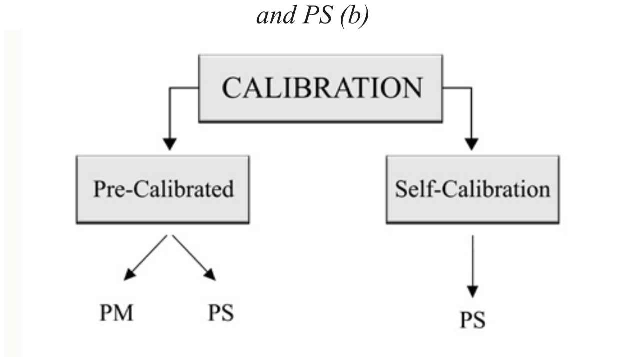



*Fig. 6. Workflow for camera calibration.*

For camera calibration the standard photogrammetric camera model that consist of two elements of interior orientation (principal distance, principal point coordinates) and of the three types of lens distortion (radial, tangential and affine) was accounted. After the calibration process all parameters were analyzed according to the camera model of PhotoScan; the parameters calculated with PhotoModeler Scanner were converted in PhotoScan standard using Agisoft Lens software. This software is necessary because various packages use slightly different camera models and parameter sets for their calibrations; these parameters are not directly comparable.

The results of camera calibration are reported in tables 3, 4 and 5; these show that the values obtained in the calibration with test field (pre-calibrated) are always very similar; instead, the values obtained by self-calibration with PS are different, particularly as regards the principal distance and the principal point coordinates. Moreover there are some differences in the lens distortion coefficients (sometimes one or two orders of magnitude); in particular in the radial distortion parameters $k_3$ and $k_4$ and in the affine distortion coefficients.

*Table 3. Camera calibration parameters for Mosaic-1.*

| | ***PM pre-calibration*** | ***PS pre-calibration*** | ***PS self-calibration*** |
|---|---|---|---|
| *c* | *7436.17 [pix]* | *7438.63 [pix]* | *7419.71 [pix]* |
| $x_p$, | *15.79 [mm]* | *15.89 [mm]* | *14.86 [mm]* |
| $y_p$, | *-14.72 [mm]* | *-15.63 [mm]* | *16.96 [mm]* |
| $K_1$ | *-9.64E-02* | *-1.04E-01* | *-1.00E-01* |
| $K_2$ | *1.51E-01* | *2.62E-01* | *2.27E-01* |
| $K_3$ | *-9.60E-02* | *-6.59E-01* | *-4.59E-01* |
| $K_4$ | *8.68E-02* | *9.48E-01* | *5.40E-01* |
| $P_1$ | *1.33E-04* | *1.31E-04* | *1.26E-04* |
| $P_2$ | *-2.63E-04* | *1.83E-04* | *-1.25E-04* |
| $B_1$ | *-4.03E-01* | *-3.92E-01* | *-1.41E+00* |
| $B_2$ | *-6.73E-04* | *9.29E-02* | *-3.87E-01* |

*c = principal distance; $x_p$,$y_p$, = principal point coordinates;*
*$K_n$= radial distortion; $P_n$= tangential distortion; $B_n$= affine distortion;*

*Table 4. Camera calibration parameters for Mosaic-2.*

| | ***PM pre-calibration*** | ***PS pre-calibration*** | ***PS self-calibration*** |
|---|---|---|---|
| *c* | *7473,17 [pix]* | *7475,99 [pix]* | *7477,82 [pix]* |
| $x_p$, | *16,57 [mm]* | *15,52 [mm]* | *15,31 [mm]* |
| $y_p$, | *-19,37 [mm]* | *-15,95 [mm]* | *-26,37 [mm]* |
| $K_1$ | *-9,81E-02* | *-9,67E-02* | *-9,99E-02* |
| $K_2$ | *1,30E-01* | *2,11E-01* | *1,98E-01* |
| $K_3$ | *-7,87E-02* | *-4,00E-01* | *-2,03E-01* |
| $K_4$ | *6,71E-02* | *4,47E-01* | *-1,82E-01* |
| $P_1$ | *1,97E-04* | *1,64E-04* | *1,34E-04* |
| $P_2$ | *-5,99E-09* | *1,71E-04* | *7,93E-05* |
| $B_1$ | *-4,74E-02* | *-3,81E-01* | *3,97E-01* |
| $B_2$ | *-1,12E-04* | *-7,22E-02* | *5,70E-01* |

*c = principal distance; $x_p$,$y_p$, = principal point coordinates;*
*$K_n$= radial distortion; $P_n$= tangential distortion; $B_n$= affine distortion;*

*Table 5. Camera calibration parameters for Mosaic-3.*

| | ***PM pre-calibration*** | ***PS pre-calibration*** | ***PS self-calibration*** |
|---|---|---|---|
| *c* | *7474.17 [pix]* | *7481.59 [pix]* | *7468.87 [pix]* |
| $x_p$, | *14.56 [mm]* | *14.81 [mm]* | *14.49 [mm]* |
| $y_p$, | *-13.65 [mm]* | *-15.28 [mm]* | *-17.95 [mm]* |
| $K_1$ | *-8.82E-02* | *-9.92E-02* | *-8.44E-02* |
| $K_2$ | *1.22E-01* | *2.58E-01* | *3.35E-02* |
| $K_3$ | *-7.22E-02* | *-7.06E-01* | *6.86E-01* |
| $K_4$ | *6.00E-02* | *1.03E+00* | *-1.95E+00* |
| $P_1$ | *1.58E-04* | *1.54E-04* | *1.67E-04* |
| $P_2$ | *-7.60E-05* | *6.55E-05* | *1.69E-04* |
| $B_1$ | *-2.71E-01* | *-6.11E-01* | *2.83E+00* |
| $B_2$ | *-2.68E-04* | *-1.67E-01* | *-1.77E+00* |

*c = principal distance; $x_p$,$y_p$, = principal point coordinates;*
*$K_n$= radial distortion; $P_n$= tangential distortion; $B_n$= affine distortion;*

Some results for Mosaic-1 are slightly different respect to the first tests [5]; these differences are due to the use of the new version of PhotoScan that has implemented a new slightly different model for camera calibration.

### *B. Images orientation*

The images orientation was performed varying the camera parameters with the aim to assess the most suitable camera calibration procedure to obtain the maximum accuracy of the final products.

Images orientation was carried out using only PhotoScan Pro (PS) software. As already described in [5] PS provides a sequence of automatic steps for image orientation and image matching with the typical SfM approach.

The workflow is divided in several steps:

- import of the different set of calibration parameters;
- images orientation with SfM approach;
- automatic/manual measurement of coded targets and scale bars;
- bundle block adjustment calculation;
- analysis of the results.

The camera parameters were kept fixed for all projects except for those obtained with self-calibration; in these the camera parameters were calculated simultaneously with the exterior orientation parameters with a SfM/bundle adjustment approach.

For each dataset three projects were created; two with pre-calibration parameters and one with self-calibration parameters.

For each project orientation was performed with SfM approach considering first 1/16 of the original image resolution (Alignment Low) without any image pair preselection for feature points detection; then, considering 1/2 of the original image resolution

(Alignment High) and the generic preselection mode that use only the overlapping pairs of photos to detect feature points. The workflow continued with the automatic measurement of coded targets and with manual measurement of the scale bars. Finally, at the end of the process, the exterior orientation parameters have been re-calculated with a bundle block adjustment considering scale bars like constrains. In the projects with pre-calibration only the exterior orientation parameters were recalculated, in the other projects with self-calibration the interior and exterior orientation parameters were recalculated.

*Table 6. Statistical results for Mosaic-1.*

| | **PM pre-calibration** | **PS pre-calibration** | **PS self-calibration** |
|---|---|---|---|
| *RMS scale distances [48 cm]* | *0.453 mm* | *0.050 mm* | *0.030 mm* |
| *RMS check distances [46 cm]* | *0.440 mm* | *0.054 mm* | *0.033 mm* |

*Table 7. Statistical results for Mosaic-2.*

| | **PM pre-calibration** | **PS pre-calibration** | **PS self-calibration** |
|---|---|---|---|
| *RMS scale distances [48 cm]* | *0.137 mm* | *0.083 mm* | *0.230 mm* |
| *RMS check distances [46 cm]* | *0.118 mm* | *0.068 mm* | *0.180 mm* |

*Table 8. Statistical results for Mosaic-3.*

| | **PM pre-calibration** | **PS pre-calibration** | **PS self-calibration** |
|---|---|---|---|
| *RMS scale distances [48 cm]* | *0.158 mm* | *0.181 mm* | *0.183 mm* |
| *RMS check distances [46 cm]* | *0.162 mm* | *0.180 mm* | *0.191 mm* |

The residuals of the scale bars have allowed to evaluate the orientation precision and to check the accuracy of the photogrammetric model. Tables 6, 7 and 8 report the root mean square of the scale bars. The results are conditioned by the different camera parameters and show some variability in the root mean square values.

In all projects generally the root mean square is included in ±0.2 mm; this value is compatible with the theoretical GSD and with full-scale representation (scale 1:1). The only exception is the Mosaic-1 datasets, where using the calibration parameters calculated with the PM values the root mean square is included in ±0.4 mm . Furthermore, in some cases it is also possible to reach accuracies of one hundredth of a millimeter.

## IV. 3D MODELING AND DOCUMENTATION

The study of the images orientation workflow is important for the 3D modeling and for the documentation of the mosaics.

Using the projects which were obtained the best results some 3D and 2D documentation products were carried out according the following steps: calculating of a dense point cloud, building a 3D mesh model, building a 3D texture model, ortho-image production.

The point clouds have been calculated taking into account both the theoretical GSD, the residuals of the orientation phase and level of detail of the final 3D model; therefore a point cloud with ¼ of image resolution was calculated corresponding to about 0.8 millimeter (Fig. 7).

*(a)*

*(b)*

*(c)*

*Fig. 7. Detail of Mosaic-1 (a), Mosaic-2 (b) and Mosaic-3 (c) point clouds.*

Three point clouds with 74 million points (Mosaic-1), 16 million points (Mosaic-2) and 63 million points (Mosaic-3) were obtained. From the point clouds were calculated respectively three meshes with 15 million polygons (Mosaic-1), 3 million polygons (Mosaic-2) and 12 million polygons (Mosaic-3).

During the point clouds build processing, for each point it is associated with the 3D position also the RGB value; the latter in the mesh generation process allows to assign to each polygon a mean value of RGB. More is defined the mesh in terms of numbers of polygons and geometry, better will be the aspect of the 3D model.

Generally, the mesh with color vertex is a product suitable for a rough idea of what is the condition of the mosaic and the type of material from which it is composed. To increase the level of detail is necessary texturize the 3D model with the images of the photogrammetric survey. Five textures of 4096 pixels x 4096 pixels were generated for each 3D model; the number of the texture was chosen to ensure a sufficiently detailed 3D model resolution to analyze even the smallest details (Fig. 8).

Finally, the ortho-images for the three mosaics were calculated with a resolution of about 2 pixels (0.5 mm). In all cases it is obtained good chromatic continuity and good definition of the details of the mosaics. Ortho-images, despite being a two-dimensional documentation, still represent the fundamental supports for the documentation and the redraw of the single *tesserae*. In fact, they allow in a very useful way qualitative analyzes on the state of degradation of the mosaics.

*(a)*

*(b)*

*(c)*

*Fig.8. Detail of Mosaic-1 (a), Mosaic-2 (b) and Mosaic-3 (c) 3D models.*

## V. CONCLUSIONS

The aspects related to the calibration phase were evaluated thanks to different sets of internal orientation parameters. The tests show significant changes between different methodologies above all for the coordinates of the principal point and for the principal distance.

Aspects related to the images orientation were evaluated on the error obtained from the scale bars used as check. The greatest accuracy was obtained for the projects where the camera calibration was resolved directly using the mosaic dataset (Mosaic-1 self-calibration) but the result show some difference among the different datasets. However, although in the other tests the residual is greater it remains in the order of the tenth of a millimeter.

In conclusion, the study proposes the definition of a workflow for the survey of mosaics with the aim to produce orthophotos and 3D models in scale 1:1. The residues obtained are compatible with products in the real object scale but some additional tests are needed to better evaluate the survey process.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