IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Lecce, Italy, October 23-25, 2017

Some considerations on measurement errors in archaeological survey

Andrea Angelini[1], Damiano Portarena[2]

[1] *Consiglio Nazionale delle Ricerche, Istituto per le Tecnologie Applicate ai Beni Culturali (Roma), Italy, andrea.angelini@itabc.cnr.it*
[2] *Università degli studi di Roma "Tor Vergata", Italy, damianoportarena@gmail.com*

***Abstract* – The aim of the paper is to evidence the measurement errors that occur during a survey, considering the current techniques used in archaeology. Some considerations are necessary in order to find possible solutions for improving the quality and the accuracy of a project. Different experimentations have been made on some case studies for evidencing differences among the methods and the related errors. A specific part has been dedicated to the photogrammetric process from drones and the errors in the representation of the archaeological areas. The processing step has been also analyzed through the use of integrated software, able to highlight issues from different points of view.**

I. INTRODUCTION

The aim of the paper is to evidence the measurement errors that occur during a survey, considering the current techniques used in archaeology. At the same time the authors provided (where possible) some solutions and suggestions for reducing the errors and checking the general quality of the work.
The main survey techniques used in archaeology and architecture are focused on range-data (laser scanning) and image-based systems (photogrammetric systems). Based on completely different geometric principles the two techniques present similar results (point clouds) [1] [2]. They are based on automated processes that do not allow an appropriate data control, like in a "black box" model. From point clouds further information can be extracted for the final representation. Graphic documentation represents the main instrument for analyzing and studying an archaeological subject and generally it is the base for the virtual reconstruction process.
Some considerations are necessary for the error evaluation generated during a survey in order to find possible solutions for improving the quality and the final accuracy of a project. The paper focuses the attention mainly on the use of laser scanner and digital photogrammetric systems but it evidences also some issues associated to the processing step. This last has been analyzed through the use of integrated software and focused mainly in the surface reconstruction and texture mapping process for the generation of a reality-based virtual model.
Some experimentations have been made on different case studies in order to highlight differences among the methods and the related errors. A specific part has been dedicated to the drones and the errors in the representation of the archaeological areas.

II. THE MEASUREMENT ERRORS IN THE SURVEY PIPELINE

The aim of a survey project and the choice of the representation scale influence directly the parameters for an appropriate acquisition phase. In addition to the instrumental error declared by the manufacturer (an untreated part), the main element to consider is the error allowed in 2D representation (besides the graphic error). It gives us information about the value beneath which it makes no sense to take measurements. This value was established in relation to the human sight (0.3 mm), so that in the 1:50 representation scale the maximum allowed error is 1.5 cm (in the 1:100 representation scale the error is 3 cm) [3]. Although the resolution and accuracy of the instruments are very high, the main error occurs during the registration of the point clouds also considering the high number of acquisitions made during a survey.
The integration of different survey techniques allows to have heterogeneous data in the same reference system but increasing the value of the general error of a project.
Still today survey methods in archaeology and architecture are based on data integration between laser scanner and topographic systems. With the aid of a total station, closed traverses are performed in order to register the scans of a survey project and to decrease the spread error of each scan of the laser [4]. The entire scan project is registered through the use of planar targets (more recently spherical targets), the Ground Control Points (GCPs). Precisely each single scan of the laser behaves like the main nodes of a total station, due to the same principle of acquisition (polar), indeed the difference consists only in the number of collected points. In topography each node of a closed traverse suffers from a

spread error that must be compensated with known formula (angular and distance compensation) [5]. The approach with the GCPs allows to reduce the mutual position of the scans in the reference system, checking the registration error of the final survey. The MSE is the error distributed on the scans based on the GCPs used during the registration phase. The choice of adequate points and their arrangement represent the main quality parameters for the registration step.

A series of algorithms for the correct mutual position of the scans have been implemented (C2C Registration). Such algorithms are known as Iterative Closest Points (ICPs) [6]. This approach allowed to change completely the procedure during the acquisition phase. At present, it is more important to have a good overlap (60-80%) among the scans in order to satisfy the requirements of the ICP algorithms. The ICP registration allows to reduce the spread error down to a few millimetres, effectively excluding the topographical survey. The risk is that the acquisition of the same GCPs with a total station would increase the registration value among the scans due to systematic errors included both in the approach on the field and during the processing step. Once the clouds have been registered a further algorithm is applied to distribute the error on the entire scan project (*bundle adjustment*).

However ICP algorithms are not able to satisfy all the conditions. Some archaeological structures need the topography to support the correct position of the scans, considering the extension and the complexity of an area. In outdoor cases the authors suggest the definition of the main traverse with a DGPS system instead of a total station used eventually only for the recognition of the target. DGPS allows to collect information of each node of the traverse with the same instrumental error (±1 cm over the entire investigated area), based only on the satellites visibility and avoiding further corrections [7].

Orienting the total station on 3 nodes of the DGPS acquisition it is possible to reference (and georeference) each new job of the scan project.

Similar problems occur also in the digital photogrammetric process (multi-stereomatching) [8][9]. In the image-based process different errors can sum up together (Fig.1):

- the dimension of the camera sensor (full frame, APS-C and the real sensor dimension expressed in mm);
- the type of lens used (fixed or zoom, preferably optic without aspheric lenses that alter the undistortion process) and the resolution of the lens (expressed in lines per mm);
- the maximum resolution of the camera (MP);
- the calibration parameters calculated from the software (internal and external orientation usually based on mathematical models and fixed chessboards);
- the appropriate data acquisition of the subject (parallel and/or convergent acquisition);
- the reconstruction algorithm used by the software for the dense cloud;
- the projection error in the scaling transformation.

A specific test has been performed on the *Facchino's Fountain* in Rome with two different photogrammetric software; *Agisoft Photoscan* and *3D Zephyr*. The same images and GCPs (5 points) have been used. The first evaluation concerned the projecting error of the numerical models. The MSE of *Photoscan* cloud is 0.0035 m, while the *Zephyr* cloud is 0.0031 m. Although the error is quite the same differences can be noticed in the dense cloud reconstruction. Measuring the absolute distance between the two numerical models in a threshold of 5 mm it is possible to notice how the reconstruction algorithm influence the final result (*CloudCompare*, Fig.2).

The histogram shows the difference between the two point clouds generated by the software. Many discontinuities are evidenced along the entire area, both on the sculpture and on the architectural part (Fig.3).

The latest photogrammetric systems generate not scaled numerical models. Two different approach are used for scaling the point clouds:

Fig.1 Dense cloud generated from image-based system with a 50 mm optic lens and 5 GCPs.

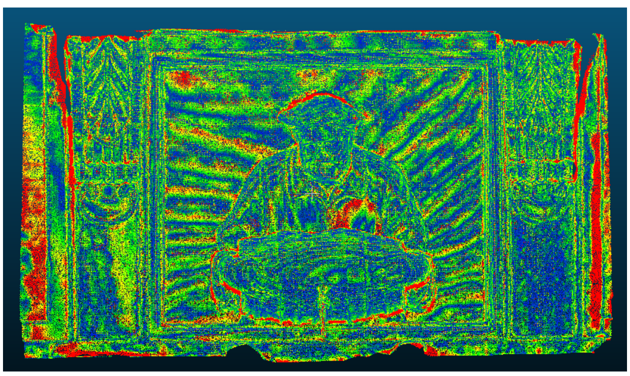

Fig.2 The approximate distance between the two clouds evidenced different discontinuities in the dense cloud reconstruction process.

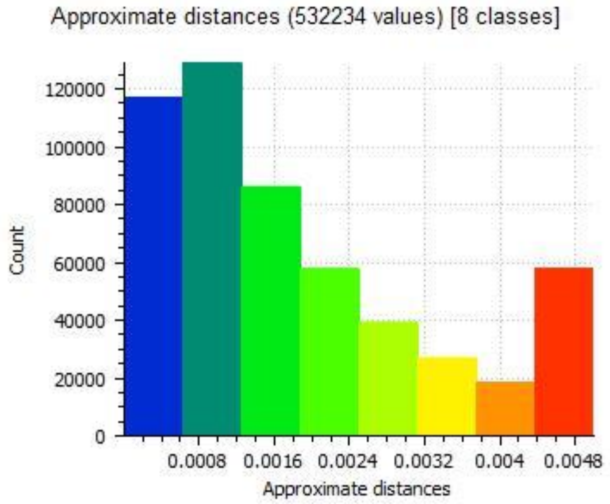

Fig.3 The histogram shows the 8 classes where points are distributed. Only a small part is included in the 1st class.

- direct measurements on the subject. This approach is less accurate because it is based on direct distance between two points of the subject;
- point coordinates. This system is based on the acquisition of specific points. Even though at least 3 points are enough to scale an object in virtual space, the scaling process needs almost 10 points well distributed on the cloud for reducing the projection error of the 3D object.

A procedure for data integration has been developed by the authors using specific tools and applying ICP algorithm to the image-based process [10]. The method allows to match together clouds of laser scanner and digital photogrammetry exploiting the properties of the ICP algorithms reducing the general spread error. Transforming the properties of the photogrammetric clouds it is possible to reach same information such the laser scanner acquisition. Different test have been performed at different scale demonstrating good results above all when the dimension of an archaeological complex influence the general accuracy in the acquisition step.

A particular attention has been dedicated to the drones and the related digital photogrammetric acquisition [11]. Drones allow to fly in critical areas and are very useful for the archaeological survey and photo interpretation; most of them are equipped with a camera and a GPS antenna for controlling the flight. Generally photogrammetric software employ *exif* information for simplifying the external orientation of the camera in space. Despite the result seems to be accurate different test performed with a drone showed how the integrated GPS increases the final projection error. The antenna is not a differential system so its accuracy is included between 1 and 5 m, depending from the satellites visibility.

Except where GPS data is corrected by a reference system (also mobile phone system), the images must be referenced with the aid of a total station or another GNSS system. A test has been performed at 10 m high with 6 target on the ground, measured both with a total station and directly on the numerical model generated by the photogrammetric software (Fig.4). The distance among the target differs from the reality of about 0.60 m. Georeferencing the model in the software the problem can be partially solved due to the constraint of the external orientation made with the GPS (general error of 0.045 m). One of the possible solution is to modify the *exif* file editing GPS information taken directly by the drone. Only in a second step it is possible to apply the point coordinates for scaling the model (general error of 0.019 m after *exif* modification).

An important issue concerns the right height for taking photo. The GSD and the representation scale are the two important factors for choosing the drone height:
- The GSD (Ground Sampling Distance) represents the relationship between the sensor width of the camera (millimetres), the flight height (meter), the focal length of the camera (millimetres) and the image width (pixel);
- the representation scale generally used in archaeology for a survey is 1:100, 1:50 and 1:20.

For the test a DJI Phantom 4 has been used. The drone has a width sensor of 6.17 mm, a focal length of 3.61 mm and an image width of 3992 pixel. At a height of 10 m the GSD is 0.43 cm/pixel, a value much more accurate than the one required. Defining the GSD in relation to the supposed representation scale it is possible to calculate

Fig.4 Ortho-rectified image of a test area corrected with total station measurements. The GSD of the image is 0.43 cm/pixel.

the right height for the drone flight. Supposing a linear dimension of the pixel of 1.5 cm (appropriate for an archaeological flight) drone should fly to 35 m high.
The GSD calculated on an ortho-rectified image is an estimated value that depends also on the geomorphology of the ground. A further consideration concerns the relationship between the rectified image and the 2D representation executed drawings the details. The archaeologist should evidence a number of details that satisfy the chosen representation scale (otherwise it is useless to have high-resolution orthophotos). The drawing is the only method based on critic approach and able to give information useful for the historical reconstruction of a monument.

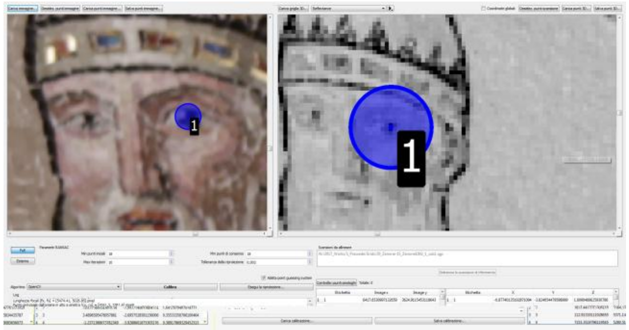

Fig.6 The different resolution between laser scanner and the related image can generate an high projection error in the calibration process.

III. THE SURFACE RECONSTRUCTION

Once point clouds have been correctly filtered, the surface reconstruction process becomes necessary to reach the final representation. Data synthesis and critic approach must be performed to achieve a good result. In this step points are filtered for the representation of the subject [12]. The process is executed through the meshing techniques. This transformation is necessary to reduce the point clouds, to create the connection among the points, to measure the connected and continued surfaces (volume and distance) and to apply different maps from the 2D images (texture mapping).
Different mesh generators currently exist even if the most common are mainly based on the studies made by Owen in 1998 [13]. The most used method for generating triangular meshes is that known as Delaunay criterion. This is therefore not just a real algorithm, but a selection criterion associated to an algorithm which subsequently generates the triangular surfaces [14].
A specific number of scans are merged together and filtered for reducing noises or incorrect points. The meshing technique is an automated procedure that does not allow the control of the interpolation. Independently from the algorithm used for the surface reconstruction the aim is to create a light numerical model with high details.
The question concerns the choice of the triangles, a value difficult to manage in the reality. How many triangles are

Fig.5 The surface reconstruction of the Facchino's Fountain in Rome. On the left a low-res model of the chest while on the right a high-res model.

necessary for an high details surface reconstruction. Four are the possibilities offered form the software (Fig.5):
- a low-res numerical model, poor of details but easy to manage in the virtual space;
- a high-res numerical model, high in details but difficult to manage with the memory of the computer;
- a multi-resolution model based on automated algorithms able to recognize and fit discontinuities on the model;
- a multi-resolution model based on a semantic subdivision of the point cloud applying a suitable meshing parameter for each architectonic or sculptural element. A point cloud can be divided in different entities such as the main walls, the columns, the capitals and altars separating the general geometry of the structure from the architectural details. The main walls need low resolution instead of the columns, the capitals and the altar that need a large number of triangles.

The result should be a light numerical model with a good number of details (semi-automatic process).
The obtained model can be modified through the optimization methods such as the smoothing algorithms that maintain the connectivity but re-arrange the nodes of the triangles and the cleanup algorithms that maintain the position of the nodes but change their connectivity. Other procedures are used to improve the final result:
- the repair of the mesh that is required when the algorithmic operation is not completely successful, so the model can have holes, or topological problems (self intersections or corners and non-manifold vertices);
- the decimation filter that uses a series of algorithms to simplify the model and generate multi-resolution models;
- the densification or refinement processes to increase the detail of the mesh. Countless are the algorithms for the densification processes (such as Edge bisection, Point Insertion, Templates).

IV. THE TEXTURE MAPPING PROCESS

The surface reconstruction is also finalized to the texture mapping process. The aim is to apply high resolution

images on the numerical model in order to map a reality-based virtual model.
Also in this case it is necessary taking images at high resolution and with a quality optic lens. Usually a 28 mm is a good compromise between shooting range and radial distortion. The shape and details of the archaeological subject influence the entire shot. The current software use similar system for performing texture mapping process, however a test has been conducted with the aid of *JRC Reconstructor* software, for the closeness to the descriptive geometry issues.
The pipeline can be summarized in the two following step:
- the full camera calibration;
- the texture mapping process on the numerical model (mesh).
The full camera calibration is performed between the image and the point cloud. The accuracy of this operation depends from the optic lens used, the number of homologous points identified and their geometric arrangement besides the different resolution of the point clouds and images (Fig.6). Same points can be described with a different number of pixels (for instance the eye of an holy character). When the resolution of the images differs far (greater/lower) from that of the reflectance model used by the laser, the projection error increases.
Despite 11 points are necessary for the full camera calibration, the authors suggest more than 20 points per image, considering the complexity of the investigated area and the level of detail. The procedure is also able to rectify wide lenses such as a 14 mm but using more than 25 points per image. A particular difficulty occurred during the recognition of the homologous points. The choice of the 3D points is done on the equirectangular projection of the point cloud (or directly on the 3D model). In this projection only the central area is useful for the identification of the points instead of the polar areas where it is impossible to see details due to their deformation. Two are the possibilities for solving the problem:
- the transformation of equirectangular projection into cubic projection with the support of specific software;
- the acquisition step made in different way (tilting the camera) considering also the poles deformation above all in the indoor space.
The authors experimented an innovative procedure with the use of Virtual Scan tool by Gexcel [15][16]. The tool is able to collect virtual scan of a subject in virtual space by using different projection systems such as orthographic, cylindrical, spherical and perspective cameras in any virtual position established from the user. For instance setting a spherical camera, the tool allows to register a new equirectangular grid (360x180) composed by the same points without altering their position (graphic card assembled on the computer can influence the resolution and reduce the elaboration time). A perspective camera has been set with the projection centre directed to the roof and with a wide FOV (Field of View, 120°). A new structured scan has been collected for camera calibration process without any deformation in the 2D structured image.
Being the full calibration a not deterministic procedure the operation must be repeated for all the images; for each calibration a new projector is created. The projector coincides with the perspective pyramid of the related image. Turning it on and off (loading the image) it is possible to view on the model the projected image and evaluate the accuracy of the process, specially on the edges and corners of the subject (Fig.7). For that reason it is important to have a light model with high details for evidencing mismatching between the projected images and the structure of the numerical model. Lighting on multiple projectors some errors can be noticed above all comparing the main features of the images. In order to reduce the mismatching it is possible to cut the images in the overlapping areas or, where possible, to detect the same points used in the full calibration step.
Once the error (pixel) allows to visualize homogeneous distribution of the image projections (no splitting images), texture mapping process can be performed directly on the mesh model. Usually a multi-blending algorithm is used

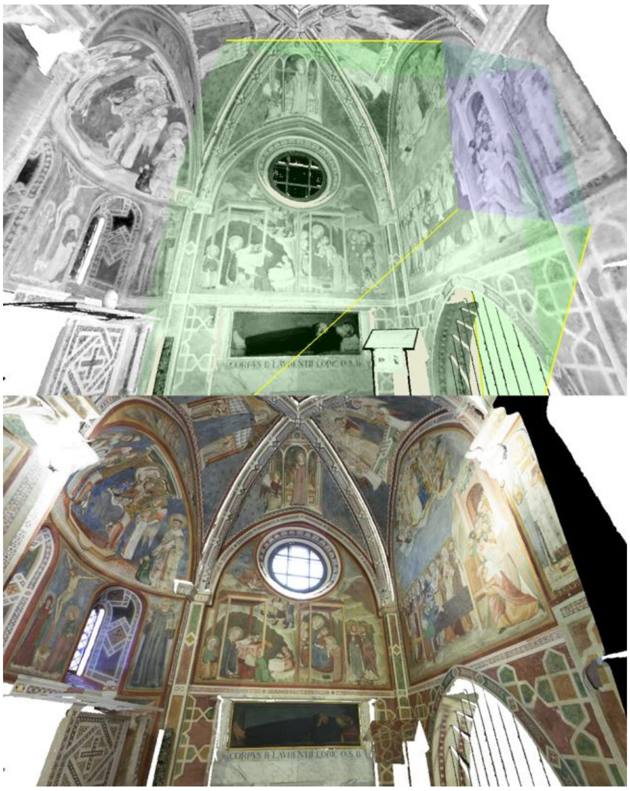

Fig.7 The texture mapping process evidences the errors above all in the edges and corners of the numerical model.

in order to correct difference in colour tone. The result is a reality-based virtual model able to describe the complexity of an archaeological subject from different points of view.

IV. CONCLUSION

The experimentations showed in the paper and the evidenced results would aid the archaeologist in the appropriate use of the technologies. The idea has been the creation of specific guidelines for avoiding mistakes and improving the accuracy of a survey project.

REFERENCES

[1] G. Vosselman, H. G. Maas, Airborne and Terrestrial Laser Scanning, Whittles, Caithness, UK, 2010, ISBN 978-1904445-87-6.

[2] F. Remondino, "Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning," Journal on Remote Sensing, 3, 2011, pp. 1104-1138

[3] M. Docci, D. Maestri, Manuale di rilevamento architettonico e urbano, Editori Laterza, Roma, 2012, ISBN 978-88-420-9068-7.

[4] W. Boehler, M. Bordas Vincent, A. Marbs, "Investigating laser scanner accuracy" in ISPRS archives, vol. XXXIV, Part5/c15, Antalya, 2003, pp. 696 – 701.

[5] M. Carpiceci, Modelli geometrici e costruzioni grafiche per il rilevamento architettonico. Idee e proposte per una migliore gestione dei dati grafici e numerici nel rilevamento architettonico, Aracne, Roma 2012, ISBN 978-88-548-5153-5.

[6] P. J. Besl, N. D. McKay, "A Method for Registration of 3-D Shapes," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 14 (2), 1992, pp. 239-256.

[7] R. Gabrielli, Introduzione all'uso dei GPS in archeologia, in S. Campana, M. Forte (eds.), Remote sensing in Archaeology, Firenze, 2001, pp. 329-354.

[8] E.M. Mikhail, J.S. Bethel, J.C. McGlone, Introduction to Modern Photogrammetry. USA: John Wiley & Sons, 200.

[9] W. Böhler, A. Marbs, "3d Scanning And Photogrammetry For Heritage Recording: A Comparison," in Proceedings of The 12th International Conference On Geoinformatics, Gävle, Sweden, 2004, pp. 291-298

[10] A. Angelini, D. Portarena, A procedure for point clouds matching from range data and image-based systems, in S. Grassini, A. Santoriello, (eds) The e-Journal of the International Measurement Confederation (IMEKO) Acta Imeko, Vol. 6 (3), 2017, pp. 57-66

[11] A. Murtiyoso, P. Grussenmeyer, "Documentation of heritage buildings using Close-range uav images: dense matching Issues, comparison and case studies," The Photogrammetric Record, 32(159), 2017, pp. 206–229.

[12] C. Bianchini, Documentation of Mediterranean ancient theatres. Athena's activities in Mérida, Gangemi Editore, Roma, 2012, ISBN 978-88-492-2524-2

[13] S.J. Owen, "A Survey of Unstructured Mesh Generation Technology", Proc. of 7th International Meshing Roundtable, Oct. 26-28, 1998, Dearborn, Michigan, USA, pp. 239-267.

[14] R. Migliari, Geometria Descrittiva. Tecniche e Applicazioni, Vol. II, 2009, ISBN 978-88-251-7330-7.

[15] M. Sgrenzaroli, G.P.M. Vassena, Tecniche di rilevamento tridimensionale tramite laser scanner. Volume 1 – Introduzione generale, Starrylink Editrice, Brescia, 2007, ISBN 978-88-89720-73-8.

[16] A. Angelini, G.. Capriotti Vittozzi, M. Baldi, The high official Harkhuf and the inscriptions of his tomb in Aswan (Egypt). An integrated methodological approach, in S. Grassini, A. Santoriello, (eds) The e-Journal of the International Measurement Confederation (IMEKO) Acta Imeko, Vol. 5 (2), 2016, pp. 71-79