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Experiences of TLS, terrestrial and UAV photogrammetry in Cultural Heritage environment for restoration and maintenance purposes of Royal Racconigi castle, Italy

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***Abstract* – The aim of the work is to describe experiences in the field of the survey of cultural heritage with the use of Terrestrial Laser Scanner and terrestrial and UAV photogrammetry. In particular, using the latest technologies, the work describes a methodology and survey techniques capable of producing 2D and 3D models suitable for subsequent restoration or maintenance work. The case study taken into consideration concern the Royal Racconigi Castle (Italy).**

I. INTRODUCTION

The digitisation of cultural heritage with appropriate surveying and modelling techniques allows to faithfully reconstruct a 3D object (in terms of position, shape and geometry) and, at same time, it is possible to extract profiles and facades in an accurate, fast and detailed way.

In general, the 3D survey can be performed using image-based 3D modelling (IBM) or range-based modelling (RBM) [1]. IBM methods use 2D images measurements in order to obtain 3D models. In particular, Structure from Motion (SfM) approach has become quite popular in Close Range Photogrammetry (CRP) thanks to ability to determine the parameters of external orientation without any a priori knowledge of the approximate positions for cameras and 3D points. SfM technique requires, in order realizing 3D models, a block of images with a high degree of overlap that capture the complete 3D structure of the scene viewed from several positions [2]. In addition, using Multi-View-Stereo (MVS) algorithm, it is possible increasing the density of the point cloud generated in SfM process. In this way, a dense and very detailed point cloud can be generated. Furthermore, the passive sensors used in the IBM method may be used even on mobile platforms (such as cranes, unmanned aerial vehicles - UAVs, hot-air balloons, etc.). In this way, it is possible to acquire data even in big, complex and inaccessible structures, such as upper parts of buildings, aqueducts, bridges etc. [3, 4].

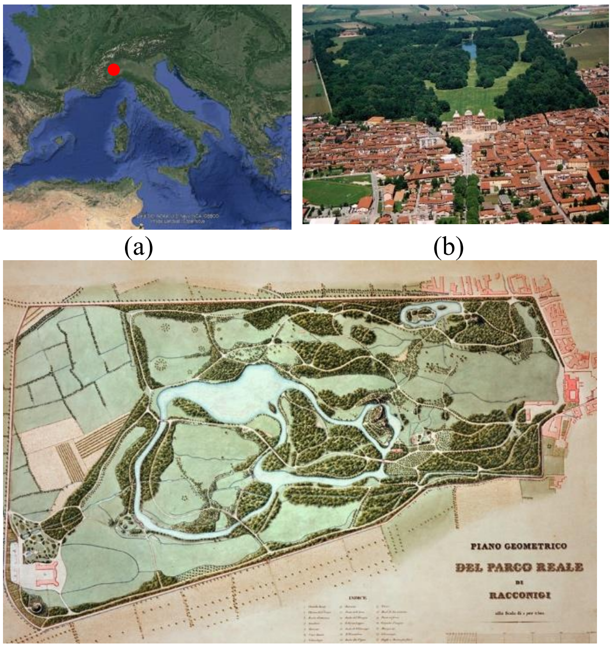
Range-based modelling is based on active sensors, which provide a highly detailed and accurate representation of a 3D object or structure. An example of active sensor is the terrestrial laser scanner (TLS). The output of a TLS is a point cloud of n observations consisting of 3D positions (x_i,y_i,z_i) $i = 1...n$ of each point in a Cartesian coordinate system with the origin in the lasers canner centre. Beyond the spatial information of each point, additional information such as colour, reflectance or normal can sometimes be associated. In general, two types of TLS are available: time-of-flight (TOF) and phase-shift (PS) [5]. In the TOF, a short laser pulse is emitted towards the target and reflected from the surface; the scanner detector measures the difference of the sending and arrival time. In the PS measurement method, the distance is determined by the phase difference between the sent and received waveforms [6]. Therefore, the CRP techniques (terrestrial and UAV) and TLS survey make it possible to obtain a dataset that can provide the metric basis for subsequent analysis, such as maintenance, restoration, conservation, construction of virtual tours, etc [7, 8, 9].

The aim of this paper is to describe actual survey methodologies, based on the use of TLS or photogrammetric techniques, and to identify a line of work able to produce 3D models, orthophotos with high geometric resolution and Computer-Aided Design (CAD) representations useful for restoration activities.

II. MATERIAL AND METHOD

A. *Case study*

The case study concerns one of the Royal Residences of the House of Savoy, the Racconigi Castle, a UNESCO World Heritage Site since 1997, which is perhaps the one that best captures the life of the court and at the same time manifests the power of the Savoy family. The adjoining park, covering over 200 hectares, with its water features, architecture, paths and atmosphere, is at the same time an expression of the royal family's leisure and holiday resort [10]. The Royal Castle of Racconigi is a palace and landscape park in Racconigi, province of Cuneo, Italy (figure 1a, b and c).



(a) (b)

(c)

Fig. 1. Study area: locating the territory on Google Earth (a); panoramic view (b) and old map of park (source: Biblioteca Reale di Torino, M-XXIII, n. Piano Geometrico del Parco Reale di Racconigi)

B. *Survey techniques and methods*

The methodological aspects addressed and described in the paper concern the terrestrial and UAV and TLS photogrammetry experiences conducted in the park of Racconigi for the realisation of digital documentation of following structure: *i)* the park; *ii)* the perimeter walls; and *iii)* some buildings present in the park. Table 1 summarizes the features of each structure.

Table 1. Survey technique used for the representation of structures

Structure	Techniques	Representation	Scale
Park	UAV photogr.	Orthophoto	1:1000
Perimeter walls	Terrestrial and UAV photogr.	(Façades) Orthophoto and CAD	1:50
Buildings	TLS	(Plans,Façades) CAD	1:50

C. *UAV photogrammetry of the park*

UAV photogrammetry allows orthophotos of complex surfaces to be obtained with high geometric resolution. The steps leading to the construction of the photogrammetric model and subsequent orthophoto of the park were: i) flight planning, ii) acquisition of the images, iii) photogrammetric processing of the images, iv) georeferencing of the model, and vi) building orthophoto and editing.

Flight planning was performed on Pix4D Capture software in order to achieve a pixel size of 2.4cm. The UAS (Unmanned Aircraft Systems) used in the survey of the Area of Interest (AOI) was DJI Mavic 2 Pro, developed by DJI Company, Shenzhen. DJI Mavic 2 Pro is a quadcopter equipped with a high-resolution colour camera (20MP, 1" sensor) [11].

In order to cover the AOI, the relative altitude (or Above Ground level – AGL) was 100m. The longitudinal and transversal overlap (overlap and sidelap) of the photogrammetric block was 80%. Once the UAV photogrammetric flight was planned, it was checked with the ENAC (Italian Civil Aviation Authority) regulations.

A total amount of 4336 images were acquired in 4 aerial missions.

The post-processing of the images of the individual blocks was carried out in the Agisoft Photoscan environment. The different georeferenced models were merged and the orthophoto with a spatial resolution of 5cm was generated.

In order to georeferenced the orthophoto, 25 targets (dimensions 100x100mm) were located and surveyed by GNSS instrumentation in Network Real Time Kinematic (NRTK) [12]. In addition to the targets, 5 natural points were measured that were easily recognisable on the ground and unequivocally identifiable on the digital images.

The coordinates of the acquired points were referred to the UTM32-ETRF2000 (EPSG:32632) cartographic system; the ellipsoidal heights were subsequently transformed into orthometric height by means of the grid IGM (*.gk2). The values reported in this grid are based on the ITALGEO2005 model, which is given an absolute accuracy of about 4 cm. The interpolation of the ground control points surveyed by GNSS was carried out by the use of Verto 2.0 software.

The Root Mean Square Error evaluated on control points was 0.025m.

Lastly, the orthophoto was edited in order to avoid perspective or unclear images, as shown in figure 2.

Fig. 2. Orthophoto of a part of the park.

With regard to the cartographic aspect, it was possible also to build a detailed DEM (Digital Elevation Model) from the 3D model (dense point cloud). This DEM, appropriately filtered, i.e. distinguishing terrain from non-terrain (trees, buildings, etc.), allowed the creation, within the ArcMap software (produced and distributed by ESRI), of contour lines with an equidistance of 1m. Moreover, starting from the DEM and identifying appropriate sections, it was possible to extract the profiles.

D. Terrestrial and UAV photogrammetry applied to boundary wall

The 3D model of the wall (external part) was carried out through the use of terrestrial and UAV photogrammetry. In particular, the terrestrial survey was carried out using a dSLR Nikon D750 camera with a 20mm fixed focal length. This made it possible to fully exploit the advantages of an image sensor measuring 24 × 36 mm, which makes it possible to render a multitude of details and details that are lost with smaller sensors. The fixed focal length lens offers a high depth of field while achieving high sharpness at all distances. Furthermore, from a photogrammetric point of view, working with a focal length means improving the quality of the image alignment process. In fact, some software such as Agisoft Metashape recommends the use of images acquired with the same focal length, at least within the dataset to be processed to produce the photogrammetric model.

In order to survey the upper part of the wall, images were acquired with UAS. The UAV photogrammetry was carried out by the use of a Parrot Anafi, a UAS quadcopter equipped with a Sony Sensor® 1/2.4" 21MP (5344 × 4016) CMOS (complementary metal-oxide semiconductor), which allows obtaining, thanks also to a 3-axis stabilizer, clear and detailed images [13, 14]. However, it was not possible to build the entire 3D model of the wall (i.e. the inner part of the wall facing the inside of the park) as there were tall trees and dense vegetation behind the wall,

The UAS flight was planned with accuracy in order to obtain a correct GSD. In addition, during the flight more attention was paid to the high vegetation present around the wall; in this task, a great contribute was provided by the sensors mounted on the UAV which signalled the possible presence of a very close obstacle.

To cover all the walls, a total amount of 8701 pictures were acquired. In particular, taking into account the shape of the wall and the number of images that can be processed in SfM/MVS software, the datasets were divided in 4 blocks.

The length of the wall is very important in relation to its height and, of consequence, a key role in the success of the photogrammetric model of these structures, is the calibration of the camera optics. In other words, incorrect values of the calibration parameters affect the entire length of the structure. Therefore, a calibration procedure in the laboratory was performed using Agisoft Lens software.

The internal orientation parameters were introduced into Agisoft Metashape. In addition, in order to minimise the influence of the quality of the photogrammetric model, sub-blocks of a length of approximately 200 metres were constructed on each side of the park. Finally, in order to increase the probability of success in the construction of the 3D model, in addition to acquiring the images orthogonally, i.e. perpendicular to the direction of development of the wall, convergent and oblique images were taken.

The post processing of the images was carried out by the use of Agisoft Metashape software. From the point of view of data organisation, 2 chunks were constructed, one for the terrestrial dataset and another for the UAV dataset. The merge of the datasets was performed through the choice of common points; to facilitate this operation of recognition of the common points, black and white targets of reduced dimensions (so as to cover as little as possible the wall texture) were positioned along the wall. After the alignment of each dataset, the point cloud was generated. Subsequently, after an operation of elimination of points not useful for the construction of the 3D model (outliers), the mesh was generated.

In order to georeferenced and scale the 3D model obtained by terrestrial and UAV photogrammetry, 250 targets (red cross) were located and surveyed by GNSS instrumentation with kinematic methodology in post-processing (stop and go). In addition to the targets, 50 natural points were taken into consideration on the walls and measured by means of integrated topographic instrumentation (total station and GNSS). In order to perform the elaborations of the acquired GNSS data, a post-processing was carried out using as known vertices those belonging to the ItalPos permanent station network (HxGN SmartNet). The processing was carried out using Leica Geo Office (LGO) software and the ellipsoidal height were subsequently transformed into orthometric using specific grid on the study area and Verto 2.0 software.

Subsequently, a top-down orthophoto of the wall was generated; in this way, it was possible to identify the various directions of the wall. This is essential in order to identify the projection planes of the orthophotos of the wall. Therefore, for each direction of the wall, it was necessary to perform a roto-translation of the GCPs. In order to speed up this operation, an algorithm in lisp was used in Autocad Autodesk environment. In this way, the model was georeferenced in a local reference system and according to the direction of development of the wall and for each of them the orthophotos were constructed with a GSD suitable for a scale of 1:50 graphic representation. In particular, 20 facades were identified, and in the case of multi-long walls, the single facade was divided into parts of 100m.

The orthophotos with a spatial resolution of 5mm were imported into the CAD environment and were positioned spatially within the graphic drawings.

Lastly, in order to improve the graphic quality of the orthophotos, a subsequent editing in Adobe Photoshop was performed. The pipeline of the several task can be summarized as follow (Figure 3).

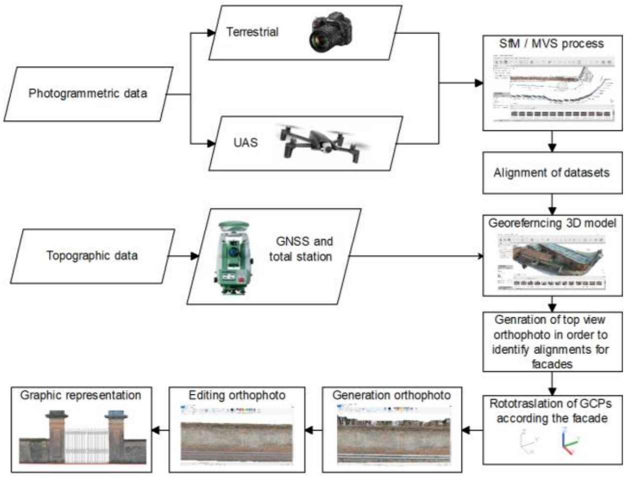


Fig. 3. Pipeline of the developed method to produce a 2D graphic representation of the wall by IBM techniques.

In addition, thin elements such as gates and iron receptions were represented with polylines; in this way, it was possible to obtain not only a clear and orderly representation but also a precise and detailed representation of the thinner elements.

E. TLS survey on the buildings related to the Royal Racconigi Castle

The architectural survey has the objective of graphically defining the reality investigated and representing, starting from rigorously acquired measurements, the geometric-morphological and constructive aspects, in relation to the identified scales of representation.

In relation to the identification of the architectural emergencies located within the park, various geomatics surveys using TLS were carried out. In this way, it is possible to obtain precise and detailed data of each building. The methodology is adapted according to the individual spatial conformations of the buildings. Following preliminary inspections, it was possible to distinguish both buildings constructed according to compositional systems that determine regular forms (on the ground floor or with a raised floor) and buildings designed to assume an irregular morphology similar to natural conformations, for blending inclusion in the landscape. This classification, depending on the physical-environmental conditions encountered during the survey activities, determines the need for integration of data from acquisition models such as aerial-photogrammetric.

In particular, the structures taken into consideration and the number of scans carried out for each one are summarized in the following table 2; in addition, for each structure, the scale of representation is reported.

Table 2. Sites and number of scans of TLS survey

Site	Number (#)
"Grotta del Mago Merlino"	25
Eremitage and snowmaking	29
"Faggionaia", originally a small neo-Gothic church	12
"Dacia Russa"	23
"Cinile"	40
"Imbarcadero" or "Darsena", for the shelter of boats	26
"Casa del Gufo"	6
Statue of Werter the dog, an animal dear to Princess Josephine	16
"Trocadero" monument	24
statue of the "Cacciatore"	29
"Colombaia"	14

For each building, a minimum and sufficient number of TLS stations were designed for data optimisation. In particular, a CAM2 Focus70 terrestrial laser scanner was used for the geomatic surveys. For the architectural surveys a total number of 244 scans were made, distinguishable according to Table 2. The processing of data acquired by TLS was performed by the use of FaroScene application [15]. In fact, in addition to the visualisation of the point cloud, the workflow provided for a filter of the data, i.e. the elimination of any noise phenomena caused by divergences of the laser beam, the decimation or elimination of redundant points [16].

Subsequently, the point cloud was assigned to a reference system. The registration of the acquired point clouds was performed by means of surface matching algorithms; in particular, the ICP (Iterative Closest Point) algorithm allows the alignment of the common parts of adjacent scans by minimising the distance between them or by using appropriately targets inserted during the survey.

The precision achieved by this process was sub-centimetric and in relation to the scale of representation required by the type of intervention.

The 3D model, although exportable in software such as Pointools or PointCab, was managed in the same Faroscene, where once a special clipping box was considered; in this way, it was possible to export several products, such as coloured point cloud concerning images preparatory to the creation of plans, profiles and façades. The choice of these bidimensional point clouds depends on the conformation of individual artifacts and is related both to the scale of representation to be adopted and to the aim of obtaining the maximum amount of information contained in the least amount of graphic processing. Actually, each single orthographic view can be obtained through the assembly of single 3D scene in order to exclude and include parts of point clouds. This task is useful for subsequent vectorization. The model can be textured to give it a chromatic connotation based on real colours.

The final phase included the reading of the information contained in the orthophotographic views in order to interpret/discretize them graphically. This task can be carried out with a specific layering and diversified for each object/case of application. The graphic dimension of the traditional orthogonal projection views, realised in vectorial CAD environment, was equipped with conventional codes and signs of the representation of architecture, inevitably related to the graphic scale of reduction.

The pipeline of the method adopted for the graphic reconstruction of the structures examined can be summarised as follows (Figure 4).

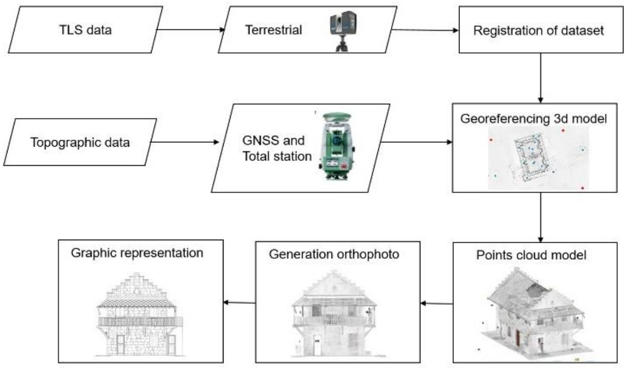


Fig. 4. Pipeline of the developed method to produce a 2D graphic representation of the architecture by TLS technique.

III. RESULTS

A. *3D models and orthophotos of the structure and buildings present in park*

The construction of the orthophotos of the site allowed the framing of the structures surveyed by photogrammetric technique or by TLS. In addition, the creation of an updated orthophoto has made it possible to identify all the natural and anthropic elements present in the park in order to define all future maintenance and management activities.

The survey and representation of the perimeter wall, which is about 7 km long, will provide an overview of the state of the damaged and compromised portions and allow maintenance and restoration work to be planned on this basis. In the graphic restitution of the wall, it was possible to identify the progressive coordinates (framed in a cartographic reference system, for example UTM-ETRF2000) in such a way as to manage all maintenance activities using the georeferenced positions subject to the intervention.

The survey of the buildings inside the park provided the documentation regarding the park for their management and maintenance.

B. *Degradation analysis using 3D models and orthophotos*

The study of degradation is a fundamental step in the restoration project. Through the use of geomatic techniques, it was possible to obtain accurate 3D models and detailed orthophotos; these models represent the basic tool for the often complex and articulated degradation analyses. Indeed, the analysis of the pathologies of degradation is necessary to choose the most suitable to the most suitable type of intervention.

As shown in figure 5, through a simple geo-referencing of structures and buildings, it was very easy to analyse them from different aspects.

(a) (b)

Fig. 5. Analysis of the state of deterioration of the wall: orthophoto (a) and 3d solid model (b).

C. *High quality of CAD representation using TLS data*

A CAM2/Faro TLS was used to survey some structures contained in the park in order to acquire the morphometric characteristics of the site. In this way, plans and façades can be constructed in great detail by means of a dense point clouds capable of reconstructing the geometry of the structure to be surveyed. Therefore, it was possible to obtain detailed 2D CAD, as shown in figure 6.

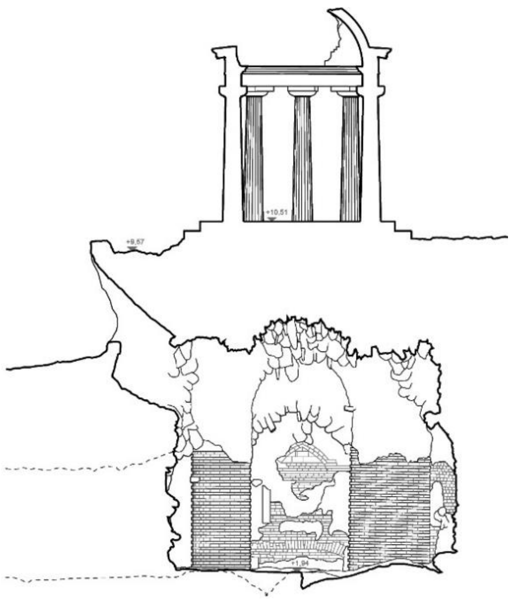


*Fig. 6. CAD representation of "*Grotta del Mago Merlino*" building.*

IV. CONCLUSIONS

The paper showed the enormous potential offered by photogrammetric techniques and those based on the use of active sensors, such as TLS, for the documentation and representation of places; this approach is particularly useful in the digitisation of cultural heritage environment. Indeed, the representation in high resolution of the park by orthophoto and the detailed and precise drawings of the several buildings by CAD and walls by orthophoto allowed to obtain an important documentation of these structures. In addition, the geolocation of structures in a UTM32-ETRF2000 reference system allows maintenance and restoration workers to identify and intervene quickly and accurately in an area undergoing intervention.

Through the TLS survey, more profiles of the point cloud were obtained and used for a graphic discretization of the information contained according to the agreed reduction scale. Therefore, for each horizontal and vertical profile, a series of coinciding and overlapping views were generated in which to include and in others to exclude the graphic information, with the aim of facilitating the hierarchization of the graphic paths produced for the final representation.

The approaches described in the paper aims to ensure that future generations can admire and use it, perpetuating its historical values without distorting or compromising its original meanings. Lastly, this activity could be perfected by surveying the green and water system components and to perform a complete documentation to support the recovery and enhancement of a World Heritage Site.

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