PRODUCTION OF HIGH GEOMETRIC RESOLUTION ORTHOPHOTOS BY PHOTOGRAMMETRIC APPROACH FOR THE ROYAL RACCONIGI CASTEL PARK DOCUMENTATION

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ABSTRACT:
The aim of this work concerns the development of a simple and rigorous procedure for the construction of metric orthophotos in high geometric resolution and rich in detail through the use of terrestrial and UAV photogrammetry techniques. This approach has been tested on various datasets relating to the Racconigi Castle (Italy) and has allowed the state of the sites to be documented. All the orthophotos produced made it possible to identify the critical areas from a conservation point of view and, at the same time, to create a support tool that makes it possible to identify, with high precision, the damaged areas in a short time thanks to the georeferencing of the processed models.

Key-words: *Photogrammetry, Orthophoto, UAV, Cultural Heritage.*

1. INTRODUCTION

The documentation of Cultural Heritage (CH) with appropriate surveying and modelling techniques allows to faithfully reconstruct a 3D object (in terms of position, shape and geometry). In addition, from 3D model, it is possible to extract profiles and facades in an accurate, fast and detailed way (Costantino et al., 2022).

The 3D survey can be performed using image-based 3D modelling (IBM) or range-based modelling (RBM). 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 (Costantino et al., 2015; Alfio et al., 2022). 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. (Adami et al., 2019; Pepe et al., 2019; Baiocchi et al., 2021). Range-based modelling, instead, 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 (Costantino et. al, 2021).

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Some studies and researches in the field of cultural heritage digitisation, use graphic representation in order to extract information from orthophotos and/or graphic restitution of the key elements of the examined structure; in this way, it is possible to build parametric and semantic models with BIM (Vach et al., 2018; Bernardello et al., 2020; Solla et al., 2020) or 3DGIS (Jedlička, 2018; Pepe et al., 2021) systems. However, the survey for 2D representation through orthophotos and Computer Aided Design-CAD continues to be a method of analysis and research in digital heritage projects (Đurić et al., 2021). Two-dimensional (2D) shape analysis techniques can be used to numerically describe the stylistic features contained in surveyed structures derived from photogrammetric models. For example, in the case of facade restoration, the experts have to map the damage and plan the corresponding measures before the actual restoration can take place; therefore, two-dimensional CAD drawings depicting each individual stone serve as a basis (Cefalu et al., 2013). Similar experiences to the one just described can be found in the field of cultural heritage. Indeed, Kan et al., 2017 wrote about of Zırnıklı Vehbi Bey Mansion building situated near to the Castle, in Turkey, showing the CAD drawings of this structure which has significantly lost its spatial integrity; the survey of this structure was performed by 3D TLS. Kouimtzoglou et al., 2017 analyse in a CAD environment the evolution of the Plaka Bridge, Greece, combining field survey data over time (1984, 2005 and 2015); the last survey campaign was carried out using SfM/MVS techniques and high quality orthorectified images of both facades of the remains of the bridge were produced. These data were in turn prepared for use in a similar way as in the ones referring to the before the collapse state in order to produce accurate 2D vector architectural drawings of the monument. Attenni et al., 2018 wrote about the important contribution given by the combination of topography and photogrammetry operations; in fact, thanks to the use of SfM/MVS software it has allowed the construction of a 2D model (orthophotos and CAD) that is metrically reliable and detailed in order to clearly distinguish the different materials and state of conservation of the structure under investigation. Donato et al., 2019 wrote about the combined methodologies for the survey and documentation of the Castle of Scalea (Italy); in order to represent the results of stratigraphic analysis, orthphoto 2D and orthoimage-based drawing was carried out. Using smartphone-based photogrammetry, Asadpour (2021) was able to reconstruct the 3D model of Historic tileworks in Ḥāfeẓ tomb, Shiraz (Iran) and, subsequently, to generate on orthophoto useful for 2D representation.

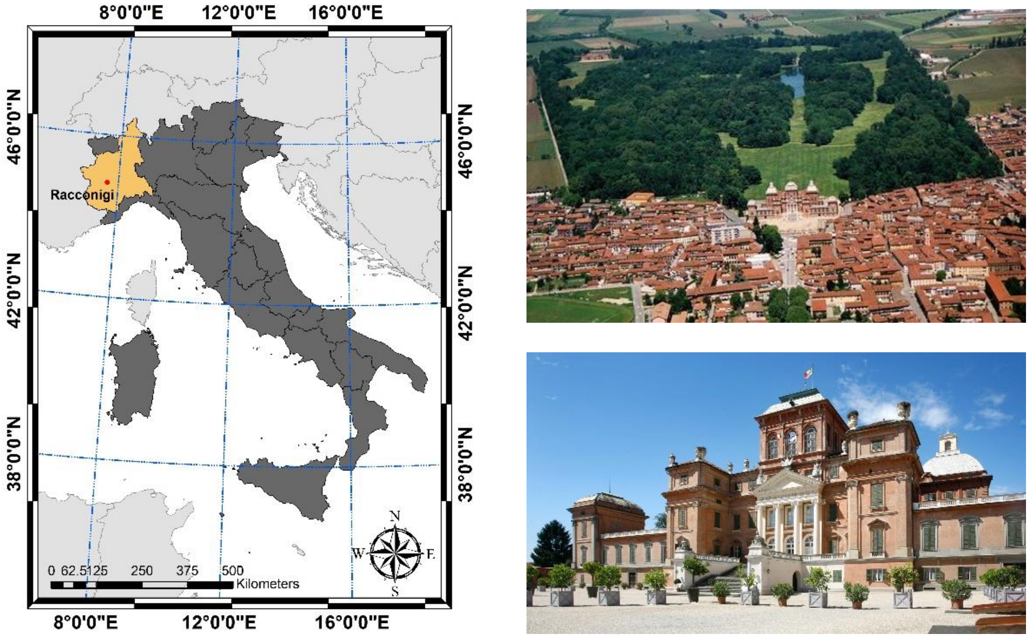
The aim of this paper is to describe actual survey methodologies, based on the use of Image based models, and to identify a line of work able to produce 3D models, orthophotos with high geometric resolution and CAD representations useful for restoration activities. This approach allows a rapid identification of the areas of intervention; furthermore, the production in sheets has the notable advantage of being easily consulted in the various phases of work, that is, from the design and planning phase to the construction phase.

2. STUDY AREA

The case study concerns one of the Royal Castle of Racconigi, 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 Royal Castle of Racconigi is a palace and landscape park in Racconigi, province of Cuneo, Italy (**Fig. 1a, b**). Founded around the 11th century as a stronghold in the March of Turin, Racconigi Castle later passed to the Marquises of Saluzzo and then to the Savoy family. Over the course of its almost thousand-year history, it has seen numerous alterations and became the property of the Savoy family from the second half of the 14th century.

The wall composed of brick elements, almost 7 km long and perimeter of a park of approximately 200 hectares - shows various forms of degradation and numerous additions made with the use of inconsistent material.

For this reason, it is necessary to produce adequate documentation to identify critical issues in the facilities and identify appropriate measures for their preservation and protection.



(a) (b)

Fig. 1. Study area: geographical overview (a); panoramic view of the park and castle of Racconigi (b).

3. DATA AND METHODS

3.1. Survey techniques and methods

The methodological aspects addressed and described in the paper concern the terrestrial and UAV photogrammetry experiences conducted in the park of Racconigi for the realization of digital documentation of following structure:

- the park; and
- the perimeter walls.

The survey of the park was carried out using UAV photogrammetry while the perimeter walls was surveyed using terrestrial and UAV photogrammetry. In this latter case, the images acquired from the ground were integrated with oblique images acquired from a UAV platform; in this way, it was also possible to cover the parts not visible from the ground.

The photogrammetric process adopted in the 3D survey is based on the use of SfM/MVS algorithms. Since geometric distortions (distortion and tangential) are generated from the ideal to the real model in the formation of the image, additional parameters (APs) must be added to the collinearity equations. In general, the Brown’s model is used in order to establish a mathematically rigorous relationship between image and object; this model taken into consideration 10 APs related to internal camera orientation (Δxp, Δyp, Δc), uncertainty about the shape of the pixel (Skew factor Sx), non-orthogonality of the reference system (shear factor Λ), radial symmetric distortion of the lenses (k1, k2, k3) and tangential distortion of the lenses (p1, p2). In this way, it is possible to write the collinearity equation as (Abdel-Azizand H Karara, 1971):

$$x_i - x_o + \Delta x = c\frac{m_{11}(X_j - X_o) + m_{12}(Y_j - Y_o) + m_{13}(Z_j - Z_o)}{m_{31}(x_j - X_o) + m_{32}(Y_j - Y_o) + m_{33}(Z_j - Z_o)}$$
$$y_i - y_o + \Delta y = c\frac{m_{21}(X_j - X_o) + m_{22}(Y_j - Y_o) + m_{23}(Z_j - Z_o)}{m_{31}(X_j - X_o) + m_{32}(Y_j - Y_o) + m_{33}(Z_j - Z_o)} \quad (1)$$

where:
x_i, y_i -measured image coordinates;
X_j, Y_j, Z_j -object space coordinates of the measured points;
X_o, Y_o, Z_o -object space coordinates of the perspective centre of the camera;
c -focal length of lens;
x_o, y_o -principal points of coordinates;
Δx, Δy -lens distortion parameters;
m_{11}, m_{12}, m_{13}, m_{21}, m_{22}, m_{23}, m_{31}, m_{32}, m_{33} - individual elements of the orthogonal rotation matrix representing the three-angle omega, phi and kappa;

At present, several software packages are available on the market that are able to reconstruct the geometry of the scene being analysed on the base of SfM algorithms. In this paper, the processing of the image dataset was carried out by Agisoft Metashape since allows to process large datasets, connect them together and perform advanced editing operations on the images. In this latter software, it is possible to build 3D models or orthophotos through a few steps: (i) alignment of the images; (ii) building a dense point cloud (PC); (iii) building mesh and (iv) building an orthomosaic. In general, before to build the dense cloud, an evaluation of the metric quality of the 3d model is performed. This task is realized taking into account GCPs and calculating the root mean square error (RMSE). GCPs are reference points easily recognizable on the images, such as intersections, manholes, antennas, marks made by tracing an X shape on the ground with spray paint, panels made of waterproof, high-contrast material (black and white or yellow and black), with a matt finish to reduce reflections and improve visibility, and coded targets (Pepe et al., 2022). In addition, target sizes are variable depending on the design GSD. The coordinate of the GCPs can be obtained by Total Station o GNSS technology. Once the GCPs have been recognised in the software and their coordinates assigned, the RMSE for x, y, z coordinates can be calculated by following formula:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(x_{i,est} - x_i\right)^2 + \left(y_{i,est} - y_i\right)^2 + \left(z_{i,est} - z_i\right)^2}{n}} \quad (2)$$

where x_i is the input value for x coordinate, y_i the input value for y and z_i the input value for z coordinate for the i–th camera position, while $(x_{i,est}, y_{i,est}, z_{i,est})$ corresponds to its estimated position.

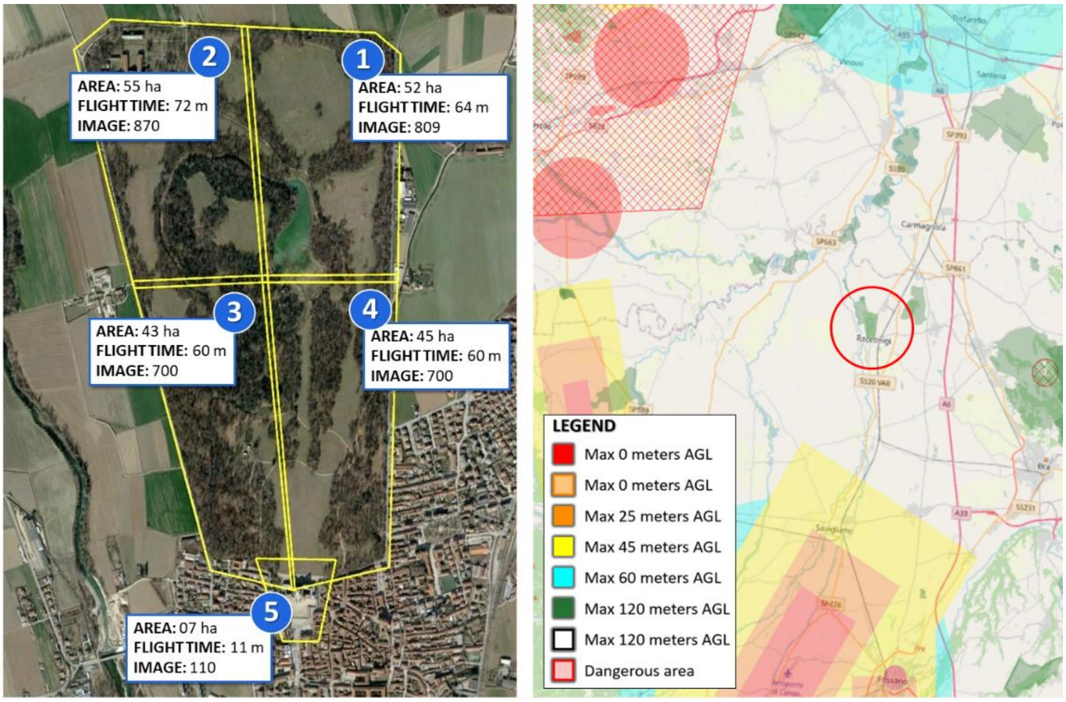
3.2. Application of the UAV photogrammetry to the park

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:

1. Flight planning;
2. Acquisition of the images;
3. Photogrammetric processing of the images;
4. Georeferencing of the model;
5. Building orthophoto and editing.

Flight planning was performed on Pix4D Capture software in order to achieve a pixel size of 2.4 cm. 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. Indeed, DJI Mavic 2 Pro, featuring the collaboratively developed Hasselblad L1D-20c, brings innovative experiences to the field with advancements in drone photography and UAV photogrammetry. The Hasselblad L1D-20c allows the user to obtain a higher standard for aerial image quality. A fully stabilized 3-axis gimbal with its powerful 20MP 1” sensor, it offers improved lowlight shooting capabilities in comparison to other drone cameras.

To cover the AOI, the relative altitude (Above Ground level – AGL) was 100m. The longitudinal and transversal overlap (overlap and side lap) of the photogrammetric block was 80%. However, to cover the AOI, five flight plans were planned (**Fig. 2a**). Once the UAV photogrammetric flight was planned, it was checked with the ENAC (Italian Civil Aviation Authority) regulations (**Fig. 2b**).



(a) (b)

Fig. 2. Flight plan scheme: flight plan blocks (a) and flight plan verification on aeronautical chart (b).

A total amount of 3189 images were acquired in 14 sessions in order to take into account the battery endurance of the UAV and ensure safety. The post-processing of the images of the individual blocks was carried out in the Agisoft Metashape environment. In order to georeference the orthophoto, 25 targets (dimensions 100x100 mm) were located and surveyed by GNSS instrumentation in Network Real Time Kinematic (NRTK). 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 cartographic system; the ellipsoidal heights were subsequently transformed into orthometric height by means by the Italian Military Geographic Institute (IGMI) grid (*.gk2). IGMI is the geographical support office of the Army and represents the Italian National Cartographic Authority. The values reported in this grid are based on the ITALGEO2005 model, which is given an absolute accuracy of about 4 cm. ITALGEO is the local geoid model for Italy that defines the relevant geoid undulation values; the most recently released and updated version of which is called ITALGEO2005. The interpolation of the ground control points surveyed by GNSS was carried out by the use of Verto 2.0 software. The different georeferenced models were merged and the orthophoto with a spatial resolution of 5cm was generated. Lastly, the orthophoto was edited in order to avoid perspective or unclear images. Regarding 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.

The orthophoto with a geometric resolution of 0.05 m is reported in the **Appendix 1**.

3.3. 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 using 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. 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, as reported in following **Table 1**.

Table 1.

Terrestrial and UAV photogrammetric datasets.

Dataset		**Images**		
		Terrestrial	**UAV**	**Total**
I	North	1413	867	2280
II	East	1810	1152	2962
III	South-West	938	400	1338
IV	West	1327	794	2121

Calibrating the camera optics is necessary if the dimensions of the wall are not proportional, i.e. the ratio of length to height is very high. In this specific case, the wall was several kilometres long and several metres high. 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. A TV with a 36" screen was used as a chessboard; the images acquired on this scene were processed within the software which generated a report not only with a plot of the radial and tangential distortion values but also of the internal parameters and additional parameters (APs).

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 using 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 (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 georeference 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 LeicaGeoOffice (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 the Autocad Autodesk environment (Costantino et al., 2020). 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 100 m. 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. According to Costantino et al., 2022, the pipeline of the several task can be summarized as follow (**Fig. 3**):

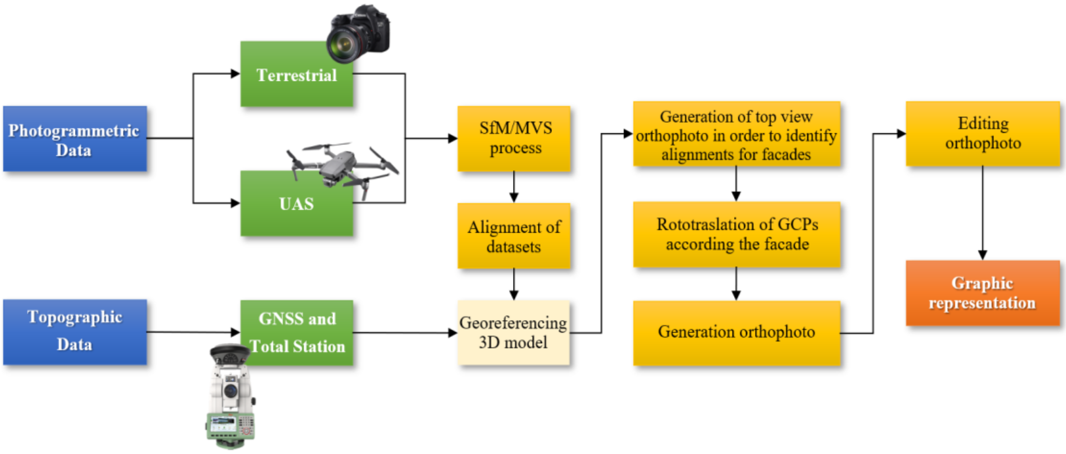


Fig.3. Pipeline of the developed method to produce a 2D graphic representation of the wall by IBM techniques.

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. Examples of graphic representation (orthophoto) of the walls around the south-west part of the park is shown in **Appendix 2**.

4. RESULTS AND DISCUSSIONS

The photogrammetric method described allowed to produce accurate and detailed orthophotos. In particular, the orthophoto of the park was realised with a geometric resolution of 0.03 m, while a geometric resolution of 0.005 m was obtained for the fence walls. In the latter case, characteristic elements such as the main entrance gate or those of the side entrances were represented by means of CAD reproduction, which allowed for a better interpretation of the state of the site.

The orthophotos in high resolution of the site allowed the framing of the structures surveyed by photogrammetric technique. 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. Once the orthophoto was built, it is possible to quickly analyse the state of degradation of the structures which is a fundamental step in the restoration project (Randazzo et al., 2021). The analysis of the pathologies of degradation is necessary to choose the most suitable to the most suitable type of intervention Therefore, the first step concerns the analysis of the state of the sites; furthermore, the possibility of easily identifying the area on which to intervene in a rapid and precise manner, not only must be the subject of study but could also be the subject of further investigations with additional sensors in specific points, such as the use of thermal cameras. For example, from the analysis of the structures, the most common surface degradation concerns the fracturing and cracking of the masonry, i.e. the phenomenon manifested by the formation of continuity solutions in the material and involving the mutual displacement of parts. The most common causes of this phenomenon are freeze-thaw cycles or failure of the supporting masonry. The contribution of geomatics in the identification of these phenomena assumes a key role. As shown in the following images (see **Fig. 4**), through a simple geo-referencing of structures and buildings it was very easy to analyse them from different aspects.

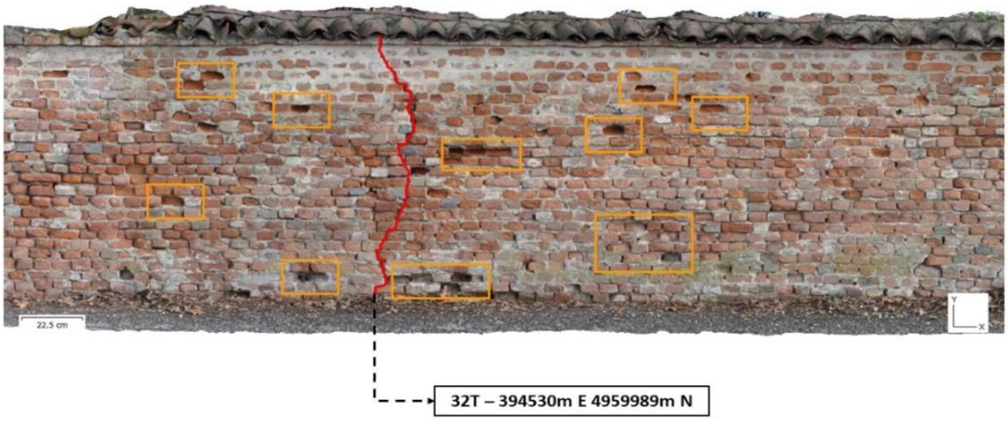


Fig. 4. Analysis of the state of deterioration of the wall on orthophoto.

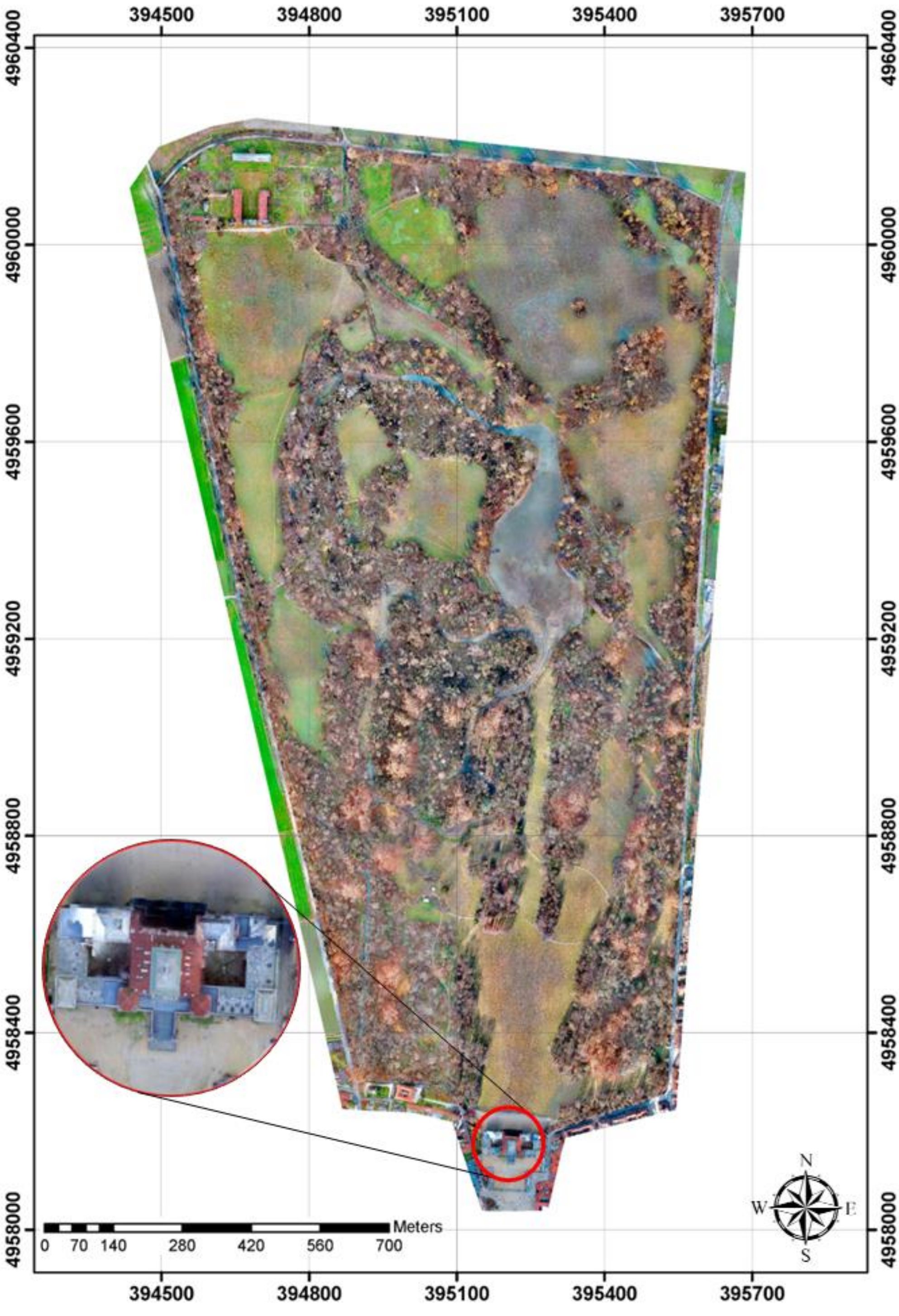
6. CONCLUSIONS

The paper showed the enormous potential offered by photogrammetric techniques 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 structure by orthophoto allowed to obtain an important documentation with elevated details. 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.

The proposed method for digitising the entire Racconigi park complex can be applied in different territorial and structural contexts related to cultural heritage. In contexts where it is not possible to acquire information by terrestrial means, UAV photogrammetry makes it possible to overcome these limitations and integrate the datasets with additional information to reconstruct a complete 3D model.

The approach 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, the study could be perfected by surveying the green and water system components and drawing up a complete documentation to support the recovery and enhancement of a World Heritage Site.

APPENDIX 1



Appendix 1. Orthophoto of the parks.

APPENDIX 2

Appendix 2.a Est side orthophoto extract.

Appendix 2.b Sud side orthophoto extract.

Appendix 2.c West side orthophoto extract.

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