Necropolis of Palazzone in Perugia: Geomatic data integration for 3D modeling and geomorphology of underground sites

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Funding information
This research was partially financed by the Cassa Risparmio Perugia Foundation

Abstract
This article presents and analyzes the methodologies and results of the survey of an Etruscan archaeological site (the Necropolis of Palazzone) with tombs dug into the ground on a slope belonging to the Perugia hill, in central Italy. The survey presented particular difficulties, since the underground rooms are numerous, small, and not illuminated, and it required the creation of a unique geometric model, including both the underground and the external area. Therefore, different techniques and tools of geomatics were used: GNSS, total station 3D survey, terrestrial laser scanning, and digital photogrammetry, with the consequent need to manage and integrate a large amount of data. It was also possible to compare the results acquired with different methods, such as the digital terrain model of the external surface obtained by unmanned aerial vehicle photogrammetry or by kinematic GNSS survey. The survey had a dual purpose: to acquire documentation of the archaeological site geometry to be imported into GIS; and to support knowledge of the geomorphologic aspects of the area, as the tombs—carved into the sedimentary formations—allow us to observe and study the local stratigraphy in detail, while the geomatic surveys put the rooms in geometric relation to each other in 3D space.
Progress in electronic and computer science, together with the development of techniques such as global navigation satellite systems (GNSSs), unmanned aerial vehicles (UAVs), terrestrial laser scanning (TLS), digital photogrammetry, as well as GIS, have brought notable advances in the traditional "topographic" survey techniques, so that they are now better described by the term "geomatics."

Geomatics consists of a multidisciplinary and integrated approach, allowing the processing of large quantities of georeferenced spatial data and information of different kinds that have to be organized, managed, and archived for a correct geometric and thematic representation of the territory.

The need to process a large amount of information with very different characteristics and formats requires complex and often dedicated systems, and appropriate software tools for spatial analysis and management of geographical data (Burrough, 1986; Burrough, McDonnell, & Lloyd, 2015; Kemp & Goodchild, 1991).

The research presented here fits into this context: the project, financed by the Cassa di Risparmio of Perugia Foundation, consists of a high-accuracy, 3D survey of the underground cavities and external ground surface of the Necropolis of Palazzone (Perugia) through geomatic methods, with two main objectives:

- To obtain a 3D geometric description of the monumental tombs; documentation useful for archaeological conservation/archiving purposes, as well as to support the touristic–cultural activities of the site.
- To provide material for further studies on the sedimentary and geomorphological aspects of the area, with a spatial reconstruction of the geological structures and lithostratigraphic units, well visible on the internal walls of the cavities, to be utilized for a paleogeographic reconstruction of the entire Perugia hill.

The project aimed to exploit the value of the 3D reconstruction and of the geological aspects to increase the scientific and touristic attraction of the site, which—despite its indisputable relevance—is located outside the "acropolis" of Perugia, devoid of strong excursion attractions, and conditioned by the presence of a freeway passing above and an adjacent railway.

In the present case, many of the most innovative techniques of geomatics have been utilized in an integrated way to carry out an accurate and detailed 3D survey of a significant number of tombs in the Necropolis, obtaining an accuracy and level of detail unattainable by traditional topographical methods (Brigante, Dominici, Fastellini, Radicioni, & Stoppini, 2009). The geomatic survey allowed us to accurately define the geometry, and relative and absolute position of the tombs, obtaining georeferenced 3D models of the cavities and ground surface on which to carry out analysis on the geomorphological and archaeological aspects (Blersch, Balzani, & Tampone, 2006). The present article focuses on the geomatic operations, with a description of the different techniques used and the results obtained.

2 | SITE HISTORY AND ASPECTS OF INTEREST

The Necropolis of Palazzone, one of the most significant Etruscan funerary sites in central Italy, is located at the south-east base of the Perugia hill, and consists of a sloping area of about 4 ha with a large number of tombs excavated in the natural ground, mostly of the Hellenistic period, in use from the sixth century BC until the first to second century BC (Cenciaioli, 2011).

Its discovery, entirely by chance, dates back to 1840, during works for the new Cortonese national road connecting Perugia to Rome, when the largest tomb in the whole Necropolis was found, later called Ipogeò dei Volumni, from the name of the Etruscan family of Velimna (lat. Volumni).

In the years following the discovery, a series of excavation campaigns were financed and brought to light approximately 200 tombs that now make up the Necropolis, many of which can be visited. The tombs, in most cases,
consist of a simple chamber, but some of them have a more complex architecture, such as the Hypogeum of the Volumni, where in addition to a central dromos, the tomb presents lateral cells and a tablinium. A significant detail of the Hypogeum is the presence of a sloping roof-shaped ceiling where figures related to the world of the dead have been sculpted.

The large number of tombs and their excellent state of conservation make the site an undisputed tourist attraction, with a high archaeological value. It is also possible to highlight another very interesting aspect, namely its value from a geological point of view.

The tombs, excavated at different altitudes within the deposits that characterized the structure of the Perugia hill, present walls that can be considered 3D geological sections, on which observations and measurements can be made, allowing us to study and describe the sediments of the hill, reconstructing the physical environment in which the soils were deposited.

The tomb layouts and their lithostratigraphic characteristics allow us to classify the Necropolis as an archaeo-geosite (Melelli, Bizzarri, Baldanza, & Gregori, 2016), a perfect combination of historical-artistic value and geological importance.

3 | GEOMATIC INSTRUMENTS AND TECHNIQUES

To plan a survey correctly, it is first necessary to establish the objectives and characteristics of the object of investigation, in order to identify the best techniques and tools to use (Tucci, Bonora, Conti, & Fiorini, 2017).

In the present case, the purpose of the survey is linked to the double aspect of documentation and research. The following purposes have been identified:

- To detect in detail the shapes and internal surfaces of the cavities both in 3D geometry and surface texture for geological purposes, obtaining an accurate documentation of the state of the site, useful for archaeological studies and conservation.
- To identify the relative and absolute position of the single cavities, so as to place them in spatial relationship with each other in a unique and well-identified reference system.
- To detect and model the geometry of the ground surface in the same 3D reference system of the underground cavities, to complete the description of the area.

The site is characterized by a sloping area with significant elevation irregularities and extensive vegetation (olive and oak trees, bushes and brambles); the hypogeal cavities, by their nature, are not visible from the outside, except in a small part, in addition to being illuminated poorly or not at all.

A survey with a synergistic use of several methodologies that complement each other (Figure 1) was conducted, creating a coordinated system that led to a complete 3D geometric description of the archaeological site (Radicioni et al., 2017).

The site characteristics made it necessary to create a very complex local geodetic network, with external and internal parts, to allow a correct geometric connection between the various tombs and the surrounding area. The reference network was realized in two levels: a first level developed in the external spaces and based on GNSS satellite measurements; and a second level reaching the underground rooms, based on 3D topographic measurements performed with a total station.

For the detailed 3D survey inside the cavities, the TLS technique was chosen, integrated with terrestrial digital photogrammetry in the case of the Hypogeum of the Volumni, the most complex and articulated tomb. A total of 19 tombs of the Necropolis, including the Hypogeum, have been surveyed in the frame of the present research work.
For the Necropolis external area and the creation of a ground surface model (digital terrain model, DTM), the digital photogrammetry technique was utilized, acquiring images by means of a UAV.

A particular aspect of this work that makes it innovative to a certain extent has been the difficulty of managing a very large amount of data, resulting from so many different methodologies, coordinating and harmonizing them with each other from a geometric point of view, the reference system and formats, in order to create final elaborations that collect and present in a unique and homogeneous way the complex geometry of the site derived from all the data put together.

Not only the development, but also the execution of the measures required careful coordination. Each phase of the complex survey had to be designed and carried out, taking into account the other techniques used, so as to allow the results to be put together effectively and maintain a consistent and homogeneous level of accuracy. Careful planning and organization of the operations made it possible to effectively coordinate the different teams of surveyors who were working simultaneously with different instruments in different parts of the site, so they did not overlap and hinder each other, and to make sure that no connection measure was omitted or forgotten.

3.1 | GNSS survey

A fundamental contribution to most geomatic surveys is given by GNSS, which allows us to accurately determine the 3D position of points, in any meteorological conditions and continuously, in a global reference system (Hofmann, Lichtenegger, & Wasle, 2008; Teunissen & Montenbruck, 2017).

In the present case, the GNSS technique was first used to determine the reference network necessary to define the 3D position of each tomb with respect to the others and to georeference the entire survey in a unique and well-defined datum.

Two Topcon GR-5 geodetic receivers, capable of acquiring GPS and GLONASS constellations, in all available frequencies and modulations, were used in three different modes:

- GNSS static relative positioning—two or more receivers held fixed on points for an appropriate time period (session length).
- Base–rover RTK (real-time kinematic)—one receiver held fixed on a known position (base) and a second one (rover) placed on the points to be measured.
- NRTK (network real-time kinematic)—the base is virtually provided by a network of permanent GNSS stations and the rover receiver is connected to the network server.
The base coordinates were estimated at ±1 cm accuracy through a static GNSS connection to the UNPG station belonging to the GPSUMBRIA GNSS network, instituted since 2005 by the University of Perugia and the Umbria Regional Council (Radicioni & Stoppini, 2019).

The RTK and NRTK techniques allowed us to obtain on the other point coordinates an accuracy which can be estimated around ±2 cm (see the RMS values in Table 1). The network used to support the NRTK technique is GPSUMBRIA, as mentioned above.

The points to be determined with the GNSS technique were materialized by small topographic nails, in order to ensure a minimum environmental/visual impact; they provided the fundamental geometric framework on which the subsequent surveys were based.

The reference system is determined by the external network to which the survey is connected. In the present case, the external network is GPSUMBRIA and the datum is ETRF2000 (European Terrestrial Reference Frame; see Farolfi, Maseroli, Baroni, & Cauli, 2009), which is the official Italian datum and allows a very good overlap of the survey with the current official maps of the area.

Furthermore, GNSS positioning was also used to validate the accuracy of the DTM of the Necropolis area obtained from UAV digital photogrammetry, measuring a relevant number of points directly on the ground surface with the GNSS technique (completely independent from the photogrammetric survey), and comparing UAV and GNSS results.

For this instance, with the same two receivers described above, a base–rover RTK survey of the ground over and around the Necropolis was performed, measuring about 500 points in the area, with an average distance of about 10 m from one point to another.

### 3.2 Total station survey

The GNSS technique is limited by the visibility of satellites, which is ensured in open spaces, while it is interrupted by solid obstacles. The underground cavities could clearly not be surveyed with GNSS; therefore, an optical-electronic total station was used to extend the network to those spaces.

A Leica TS-06 total station, characterized by an accuracy of 2" on angles and 2 mm on distances, was used for this phase of the survey, setting in station and orienting it on the points previously determined with GNSS. All points measured with the total station were finally georeferenced in the same datum as the GNSS points (ETRF2000). The distances involved for the total station connections were very short (some tenths of meters), so it is reasonable that the estimated accuracy in the absolute position of the GNSS points (±2 cm) was maintained for the total station measured points.

### Table 1 Kinematic GNSS precision

|                  | Base–rover RTK | Network RTK |
|------------------|----------------|-------------|
|                  | Horizontal RMS (m) | Vertical RMS (m) |
| MAX              | 0.020           | 0.019       |
| MIN              | 0.005           | 0.006       |
| MED              | 0.009           | 0.009       |
|                  | 0.025           | 0.030       |
|                  | 0.007           | 0.009       |
|                  | 0.013           | 0.015       |
In addition to allowing the connection between the outside and inside network vertices, the total station was used to measure a large number of targets, necessary for the orientation of the laser scans (see Section 3.3).

The overall network, very articulated, is composed of five subnets, which connect 19 GNSS vertices to 30 external and underground points measured with the total station (Figure 2).

**FIGURE 2** Necropolis reference network: GNSS vertices and connections are represented in red; total station connections in blue; targets are black

3.3 | Terrestrial laser scanning

Laser scanning, one of the most powerful and productive 3D geomatic survey techniques, is capable of measuring a large number of points in a very short time, performing a 3D scan of the object (Remondino, 2011; Tucci, Bonora,
This technique was used for detailed survey of the cavities, scanning the Hypogeum of the Volumni (Figure 3) and another 18 tombs, with a total of more than 60 single scans.

The survey was executed by means of a FARO FOCUS 3D X130 laser, equipped with an integrated digital camera capable of acquiring RGB color values simultaneously and in a geometrically coordinated way with scanning. The instrument has an average resolution (scanned point geometric interval) of about 12 mm at 10 m, and an acquisition time of about 10 min/scan.

A particular problem with the survey in question was the fact that the underground rooms were for the most part completely unlit. This is generally not a problem for laser scans per se, since the laser itself “illuminates” the subject and is able to detect the geometry even in complete darkness. However, we wanted to associate the geometry with radiometric information, obtained from the digital camera incorporated in the scanner; in particular, to be able to see clearly the stratigraphy on the walls for further studies by geological colleagues. The problem was solved by using LED lights. These spotlights had to be arranged so as not to be seen directly by the camera of the scanner, because they would have caused a dazzling and burning effect; it was therefore arranged to place them on the legs of the tripod of the scanner using specially constructed adapters, so that the spotlights remained in the shadow of the scanner, illuminating only the surrounding scene. To obtain uniform illumination, it was necessary to use a minimum of four spotlights simultaneously.

**FIGURE 3** Hypogeum of the Volumni point cloud from TLS survey
The 60 scans were oriented with respect to each other by performing a roto-translation in space, made possible by the presence of a certain number of common points between the adjacent scans (at least four). The common points were realized by means of an adequate number of rectangular flat targets with a checkerboard pattern and a set of six calibrated spheres.

The target coordinates were determined in the ETRF2000 datum by total station measures. Thus, the spheres were utilized only for a relative orientation, while the targets permitted both a relative and an absolute orientation in ETRF2000.

From the assembly of all individual scans, we derived an overall point cloud. In the present case, this was composed of about 900 million points with a point density of the order of 1 cm. We then performed an accurate orientation of the overall cloud, in order to express all point coordinates in the ETRF2000 datum. The procedure consisted in a spatial roto-translation of the assembled cloud with respect to the known 3D coordinates of the targets.

Table 2 shows the residuals on the target coordinates of the final roto-translation of the assembled laser scanner. The residuals on the targets are all under 1 cm, indicating good agreement between the TLS survey and the reference points determined with GNSS and total station, congruently with the absolute position accuracy of ±2 cm estimated for the reference points. The accuracy in the relative position of the TLS survey points within each cavity is estimable at subcentimeter level.

From the 3D laser point clouds, a series of detailed vector drawings (CAD) were obtained, consisting of plans, sections, and internal elevations (Figure 4). Such “conventional” graphical elaborations can easily be used by technicians for documentation and investigation in different areas (Conservation, Restoration, Geology, Archaeology, and Engineering).

The clouds of points correctly georeferenced in planimetry and elevation, with their inside walls textured point by point by means of the high-resolution digital images acquired by the scanner, allowed our geological colleagues to perform in-depth studies on the stratigraphy of the site that allowed us to increase and update our knowledge on the geomorphology of the Perugia hill. The results are presented in scientific papers, among which we mention the following: Melelli et al. (2016, 2021), Bizzarri, Melelli, and Cencetti (2018).

| Target ID | (E, N, H) residuals (m) |
|-----------|--------------------------|
| 226       | (0.003, 0.003, −0.002)   |
| 254       | (−0.003, 0.000, −0.001)  |
| 224       | (0.002, −0.004, 0.001)   |
| 223       | (−0.004, −0.001, 0.001)  |
| 221       | (0.001, −0.008, 0.000)   |
| 225       | (0.001, −0.009, 0.001)   |
| 245       | (−0.003, 0.000, 0.000)   |
| 201       | (0.001, 0.004, 0.001)    |
| 203       | (0.000, 0.005, 0.000)    |
| 246       | (−0.003, 0.000, 0.001)   |
| 222       | (0.003, 0.005, −0.002)   |
| 200       | (0.002, 0.004, 0.001)    |
| Max residual (m) | Min residual (m) | RMS (m) |
| 0.005 | −0.009 | 0.003 |
3.4 | UAV photogrammetric survey

Besides the geometry of the underground cavities, even if assembled together, it remained to model in detail the ground surface of the Necropolis and the surrounding area, and connect the external 3D model to that of the underground spaces. The large extension of the area and the considerable presence of vegetation would have made it very difficult to use the TLS technique again. For this reason, it was decided to define the geometry of the ground surface through an aerial photogrammetric survey with digital images acquired by a UAV (Mancini et al., 2013).

In the specific case, a SenseFly EBee fixed-wing drone was used; this UAV, equipped with an 18 MP digital camera and a GNSS receiver, is very light (about 700 g), so as to be considered harmless. Camera data are shown in Table 3.

**FIGURE 4** Vectorial CAD section of Hypogeum of the Volumni

**TABLE 3** UAV camera data

| Camera name       | Canon S110          |
|-------------------|---------------------|
| Camera type       | frame–pinhole       |
| Focal length (mm) | 5.394               |
| Principal point X (mm) | 0.000               |
| Principal point Y (mm) | 0.000               |
| Pixel size (mm)   | 0.001860            |
| Sensor width (mm) | 7.440               |
| Sensor height (mm)| 5.580               |
A total of 140 frames were acquired, at a height above ground variable from 110 to 130 m, in order to take into account the slope of the area, realizing an average GSD (ground sampling distance) of about 4 cm.

The flight plan consisted of two subsequent flights, in two directions: the first NE–SO and the second, immediately following, in the orthogonal direction, maintaining a cross-track overlap of 60% and an along-track overlap of 70%.

The resulting flight path can be seen in Figure 5; it is composed of eight strips in each direction, for a total of 140 images.

A set of 25 targets (30 × 20 cm in size) with checkerboard pattern were positioned on the ground, with a homogeneous distribution, to be used as ground control points (GCPs). The target coordinates were determined through the base–rover RTK GNSS technique in the ETRF2000 reference datum, in a quite similar manner to other network markers.

After importing the images and identifying the GCPs, the photogrammetric process performed the orientation (aerial triangulation) automatically, dividing it into several phases: feature search and matching, bundle block adjustment (Casella, Chiabrando, Franzini, & Manzino, 2020). The photogrammetric processing was carried out by means of the Menci APS software (Qin, Gruen, & Fraser, 2014).

The UAV GNSS coordinates of the perspective centers, even if approximate (no differential correction had been applied) were used as starting data in the bundle block adjustment calculation. Once the automatic phase was completed, the set of GCPs was imported into the project in order to improve the quality of the external orientation.

The complete aerial triangulation report contains detailed information, including:

- number of rays per point
- number of rays per image
- recalculated 3D coordinates of the points

**FIGURE 5** UAV flight path
• residuals of the points in image coordinates
• overall RMS
• residuals of the control points in meters.

A summary of the quality parameters of the image processing is shown in Tables 4 and 5.

From the processing of the images, a 3D digital model of the ground surface (DSM), including vegetation and buildings, was obtained, georeferenced in ETRF2000. It was automatically converted by the software into a point cloud (Figure 6) with RGB color attributed to each point from the images (James et al., 2019).

A DTM in raster format was then derived from the DSM, removing vegetation and buildings by filtering procedures (Mendes, Henriques, Catalão, Redweik, & Vieira, 2015). The point cloud acquired from the UAV photogrammetric process was finally assembled with the cloud obtained by the TLS survey (both were georeferenced in ETRF2000), realizing an overall 3D model (Figure 7).

The use of a rotary-wing UAV with a greater resolution camera would probably have proved more efficient by ensuring greater stability in flight and a better image resolution. However, in the present case the use of a very light fixed-wing UAV allowed us to overcome the difficulties related to the conduct of a flight in an area subject to strict rules, given its proximity to an airport and a freeway.

4 | DTM COMPARISON AND FURTHER ELABORATIONS

The DTM accuracy assessment methods through control points are well-defined in technical publications, such as the guidelines by Brovelli et al. (2020), and scientific papers such as Barazzetti, Brovelli, Cilloccu, Melis, and Vacca (2007). In the present case, some simplified procedures were used, but essentially following the spirit of the publications cited above.

| TABLE 4 UAV processing data |
|-----------------------------|
| Data defined for adjustment  |
| Images                      | 140 |
| Exterior orientations       | 140 |
| Object points (total)       | 6,982 |
| Intersection points         | 6,957 |
| Control points              | 25  |

| TABLE 5 Residuals of UAV image processing |
|------------------------------------------|
| Residuals on image points (all images)   |
|                                          |
| RMS of residuals                         | 1.79 | 1.77 |
| Average of residuals                     | −0.07 | 0.09 |
| Residuals on ground control points       |
|                                          |
| RMS of residuals                         | 0.031 | 0.037 | 0.043 |
| Average of residuals                     | −0.002 | 0.003 | −0.012 |
A first comparison was performed by means of some functions included in the Leica Cyclone software. The UAV DTM raster file was imported into QGIS and a point cloud was generated from it by means of the QGIS processing function, which converts from pixel raster to points. The point cloud obtained was then imported into Cyclone.

The ground points measured with the GNSS RTK technique, also imported into Cyclone, did not coincide with the nodes of the DTM grid (approximately 20 × 20 cm), so a direct comparison was not possible. Each GNSS elevation was then compared with the average of the four surrounding DTM values, weighted by the inverse of the distances between the GNSS point and the four grid nodes.

From a statistical analysis carried out on the height differences computed as above, the following results were obtained:
• average difference = −0.06 m
• median = −0.05 m
• maximum negative deviation = −0.38 m
• maximum positive deviation = +0.38 m

The height difference distribution is illustrated by the histogram in Figure 8. About 70% of the points present a maximum absolute difference of 10 cm or less, in agreement with the altimetric accuracy of the UAV photogrammetric survey, estimated at ±10 cm.

Through the QGIS environment, further elaborations were carried out in order to compare the GNSS measured points with the data deriving from UAV (Burrough et al., 2015; Noti, 2014).

First, a raster DTM was created using the Interpolator.TIN plugin by entering the points vector layer of the GNSS ground survey and the contour lines of the CTR (Carta Tecnica Regionale, an official technical map at 1:5,000 scale) of the area as input data. The plugin allows us to generate triangulated surfaces. The result of the process was a raster DTM with a pixel size of 20 × 20 cm.

The GNSS point-generated DTM described above was subsequently compared with that obtained by UAV photogrammetry through CloudCompare software, which allows us to manage and analyze point clouds, shape-files, text files, and meshes (Ahmad Fuad, Yusoff, Ismail, & Majid, 2018; Lague, Brodu, & Lerou, 2013).

The analysis calculated the distances between the points of the two clouds through the Cloud/Cloud (C2C) distance command, with particular reference to the Z coordinate. The C2C distance computation tools calculate

![Figure 8](image-url)  
**Figure 8** Relative frequency of the differences between GNSS and UAV DTMs
distances between a reference cloud and the compared one, with a nearest-neighbor method. This algorithm searches the nearest points in the reference and comparison cloud, and determines their Euclidean distance. As reference cloud, the UAV DTM was used. The result is a map of the differences between the two clouds (Figure 9), in which the Z-difference spatial distribution is represented.

At first glance it can be seen that the major errors are concentrated near the edges and in those parts where points were not surveyed with RTK positioning, while in most of the area there is an error of less than 40 cm. The

**FIGURE 9**  C2C distance computation of DTM point clouds. On the right, the histogram of the height differences distribution

**FIGURE 10**  Slope map from RTK DTM (left) and UAV DTM (right)

**FIGURE 11**  Exposure map from RTK DTM (left) and UAV DTM (right)
The histogram (on the right in Figure 9) shows that most of the differences (around 70%) fall within the range between −40 and 40 cm, with a mean value of −0.046 m. For further analysis, the slope, exposure, and contour line maps were then obtained from the raster DTMs using some other QGIS functions and plugins.

The slope maps were created through the raster geomorphological analysis–slope function. The result is a grid with values expressed in degrees that represents the gradient (first derivative) of the morphological surface; the
algorithm determines the value of the slope of single cells using the elevation data of one cell and the surrounding ones (see Figure 10).

The exposure map is also significant for defining a slope orientation with respect to north. Using the direction of maximum slope, the calculation determines the orientation value for each single cell measured from 0 to 360° clockwise from the north. The exposure maps were generated through the raster geomorphological analysis–aspect function, and the result is shown in Figure 11.

To obtain contour maps from the DTM derived from the ground survey, the raster extraction–contour lines command was used, setting a height interval of 1 m. The contour lines obtained this way were compared with those extrapolated from the UAV survey directly from the Menci APS software. The result is presented in Figure 12, showing a substantially good agreement between the two models.

Finally, some altimetric profiles were extracted through the QGIS plugin profile tool along polylines. As can be seen from Figure 13, profiles of the area along orthogonal directions extracted to the two DTMs under comparison are in quite good agreement with differences of less than 40 cm, confirming the previous results.

5 | CONCLUSIONS

The use of GNSS and geomatic techniques, providing an accurate reconstruction of the geometry and location of the tombs, has made it possible to appreciate the archaeological site in its three-dimensionality, highlighting the distribution of the cavities and their space relation both in planimetry and in altitude.

By means of different geomatic techniques that integrate and complement each other, and through a complex integrated data management process, we have produced a 3D survey with an average accuracy of about ±2 cm in absolute coordinates. The relative accuracy of the TLS surveys inside each single underground cavity can be estimated at a better level, of <1 cm. The survey has been georeferenced in the ETRF2000 datum by means of GNSS connections to an external permanent stations network (GPSUMBRIA).

The final 3D model of the archaeological site has been obtained by assembling the TLS models of the tombs and the photogrammetric model of the external ground surface. From this 3D model it is possible to obtain metric information by tracing horizontal, vertical, or inclined sections in any part of interest.

The overall 3D model, "navigable" and easily available and distributable, realizes a very effective archive documentation of the actual state of the Necropolis, and constitutes a detailed source of information on which investigations at multiple levels and in various fields (mainly Archaeology and Geomorphology) can be carried out. Further analyses conducted in the QGIS environment regarded the comparison of the DTM obtained through UAV photogrammetry with that derived from a GNSS RTK control survey.

This work shows an example of how the integrated use of advanced techniques of geomatics can be useful for accurate and detailed reconstruction and documentation of a complex archaeological site, including external and underground parts, supporting multidisciplinary investigations.

ACKNOWLEDGMENTS

The authors would like to thank the Cassa Risparmio Perugia Foundation, which co-funded the project; the scientific manager of the project, Professor Corrado Cencetti and Professor Laura Melelli of the Department of Physics and Geology, University of Perugia and all staff members; the Superintendence of Archaeology, Fine Arts and Landscape of Umbria, which granted the authorization to carry out surveying of the Necropolis area; and all the staff of the organization who facilitated the group in any way; also Eng. Andrea Brozzi for his kind help during the measurement campaigns. Open access funding enabled and organized by Universita degli Studi di Perugia within the CRUI-CARE Agreement.

CONFLICT OF INTEREST

The authors declare no conflict of interest.
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How to cite this article: Radicioni, F., Stoppini, A., Tosi, G., & Marconi, L. (2021). Necropolis of Palazzone in Perugia: Geomatic data integration for 3D modeling and geomorphology of underground sites. Transactions in GIS, 25, 2553–2570. https://doi.org/10.1111/tgis.12818