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An integrated survey system for the Nuraghe Sa Jua, Sardinia, Italy

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ABSTRACT

The paper describes the results obtained following a three-dimensional survey on the Nuraghe Sa Jua in Aidomaggiore (west-Sardinia, Italy), in which two high-resolution methodologies - the Laser Scanner survey and the drone aerophotogrammetry - were integrated. The nuraghe's documented problem pertains to the detachment of some wall ashlars near the stairwell, which may create a risk of structural collapse and subsequent loss of the archaeological asset. The main goal of the study is to ensure visitor's safety, the conservation of the heritage site, and the enhancement of its value. The integrated survey serves as a first step towards a better understanding of the asset's safety requirements and architectural restoration. The accuracy of surveying by means of a 3D laser scanner was complemented with the use of drone digital photogrammetry, which enabled the surveying of areas that would otherwise have been inaccessible, whilst ensuring safety for the operators, the equipment, and the monument itself. A series of 2D graphic drawings were created using open-source software, producing high-quality 3D models and accurate orthophotos, which are measurable, and which can be easily interpreted by the client who commissioned the survey work. The results demonstrate the cost-effective advantages of using high-resolution techniques for archaeological conservation.

1. Introduction

In order make this section easier to be read, the introduction is organized into in two sub-sections dealing on Nuragic buildings and state-of art of surveying methods respectively.

1.1. General overview of nuragic buildings

The over 7000 nuraghi which still stand in Sardinia are an extraordinary example of cyclopean architecture that spread during the Bronze Age (Lilliu, 1962), particularly in the Middle Bronze Age (17th-14th century BC) with the construction of protonuraghi or corridor nuraghi, and in the Late Bronze Age (14th-12th century BC) with the spread of classic or tholos nuraghi. The term "nuraghe" gave its name to the Nuragic Civilization, which had its cultural roots in the earlier Early Bronze Age and Sardinian Eneolithic. In the first phase, we see the construction of cyclopean structures of irregular shape (subcircular, subelliptical, reniform, etc.) with poorly developed internal spaces, sometimes reduced to niches or corridors with a non-linear layout, with buildings whose masonry mass occupies most of the volume. In the following phases, there is a progressive improvement in construction techniques, with a tendency to build truncated conical towers, with masonry that increasingly leaves space for rooms and with more sophisticated architectural solutions: such as overlapping tholos chambers, stairs carved within the walls, and large corridors. In the Late Bronze Age, there was an explosion of the Nuragic architectural phenomenon, with the development and experimentation of original solutions, ranging from the simple nuraghe with a single tower to the more complex monuments, consisting of multiple towers, courtyards, and perimeter walls. Complex nuraghi are sometimes the result of modifications, additions, and renovations over the centuries: in some cases, the oldest nuraghi were incorporated into complex structures, and adapted to different needs over time (Su Mulinu of Villanovafranca, Sa Prisgiona of Arzachena); in other cases, it can be said that at the base of a complex nuraghe there is a true original project (Santu Antine of Torralba, Nuraghe Arrubiu of Orroli), in other cases still, as needs changed, a single-tower nuraghe could become a complex nuraghe (Vanzetti et al., 2013; Cossu et al., 2018).

It is generally believed that in the later phases of the Final Bronze Age and the Iron Age, no new nuraghi were built, but significant restructuring and modification works were carried out on the monuments; during this period, there is a progressive increase in the

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importance of the structures present in the villages. The Nuragic society undergoes significant transformations due to a change in the geopolitical balance in the Mediterranean. The nuraghe loses its original function, becoming almost a symbol of a mythical and archaic society, as evidenced by the modifications to the spaces and their intended use: some rooms became places of worship like Su Mulinu of Villanovafranca or Nurdole of Orani, others are modified or integrated into villages or sanctuaries, like Santa Vittoria of Serri. One of the most evident aspects of this transformation is the discovery of bronze and stone sculptures representing nuragic towers, often in environments that were intended for community assemblies, such as the meeting hut of Palmavera in Alghero, almost as if the nuraghe had become an object of worship and a symbol of Nuragic society (Campus and Leonelli, 2012). Nuragic architecture was also expressed in many other forms: temple buildings (megaron, temples in antis), wells and springs, giants' tombs, massive walls, extensive villages (Moravetti et al., 2014, 2017).

1.2. State of the art of surveying methods

A range of integrated high-resolution equipment is used to study the conservation status of these structures; this has become a widely applied practice in the archaeological areas of Sardinia, resulting in excellent outcome in terms of cost, quality and ease of use. It is possible to produce 2D and 3D graphical processing of high quality and reliability Through the processing of the point clouds obtained from laser scanners and drones. In particular, the 3D model obtained from aerial images from drones, appropriately georeferenced, by utilising a GPS instrumentation in RTK mode for beating GCPs, or images derived from terrestrial photogrammetry, resulted in a centimeter-scale resolution comparable to the sub-centimeter resolution of a medium-to-high quality laser scanner-derived product, which is extremely useful for understanding and documenting the dynamics of the formation of archaeological deposits and for surveying architecturally complex structures, such as nuraghi, domus de janas, sacred wells, etc. (Dessì et al., 2015; Mannu et al., 2015; Marcialis, 2015).

Documentation of archaeological heritage (graphic, photographic and three-dimensional) is a fundamental tool for their preservation (Costa-Jover et al., 2019). Current massive data acquisition techniques are particularly useful for ancient buildings, especially those with complex configurations, since many building elements are not easily accessible (Lerma et al., 2010; Marcialis and De Martini, 2024). The technique has also achieved important results in specific areas such as those related to megalithism (Velli and Velli, 2017; Marcialis, 2020) and funerary hypogeism (Marcialis, 2015; Furfaro et al., 2022).

Terrestrial Laser Scanning (TLS) allows the survey of complex spaces in a short time and with great accuracy (Vezočnik et al., 2009). Numerous investigations have tested the reliability of the technique for surveying a building (Park et al., 2007; Berenyi et al., 2010). Currently, TLS is used not only in the fields of archaeology and civil engineering, but also in geology (Buckley et al., 2008), geoengineering (Li et al., 2019) and mining (Francioni et al., 2015; Eyre et al., 2016). In building and construction sectors, TLS surveys have various applications, such as the diagnosis of structures and their constituent materials (Fais et al., 2018; Suchocki and Błaszczak-Bąk, 2019). Pesci et al. (2011) evaluated in detail the deformations of two towers in Bologna (Italy), with in particular regard to the deviations from a regular inclination of their walls, by using TLS. Quagliarini et al. (2017) applied TLS to assess the deformation of the inner vaults subject to their own weight as well as the main façade of Santa Maria in Portonovo (Italy) church. Hinzen et al. (2013) surveyed the inclination of the seating rows of the Roman theater in Pinara (Turkey) which was damaged by seismic activity. Underground structures can also be easily studied with TLS (Porras-Amores et al., 2019).

Laser scanning enables the processing of a simple form of 3D model: a set of 3D coordinates sampling the surface of an object, called a point cloud (Vacca et al., 2012). TLS used in archaeology can be of the TOF (time-of-flight) or phase difference type, based on the measurement method (Bartolucci, 2009). Digital photogrammetry, better known as Structure from Motion (SfM), is a technique that allows measurements to be obtained using images acquired from a sensor (Erenoglu et al., 2017); it has long been used in archaeology (Fujii et al., 2009), even with the use of the more traditional aerostats balloons (Nieddu, 2014), in part due to the widespread use of affordable software (Fernández-Hernandez et al., 2015). Modern photogrammetry and remote sensing have identified the potential of images from Unmanned Aircraft Vehicles (UAVs) over the past decade (Lambert and Jacob Skousen, 2023). Photogrammetric surveying has developed its traditional acquisition and processing method with the help of advanced technology from Unmanned Aerial System (UAS) (Stanga et al., 2023).

Continuous improvement in artificial intelligence-based technologies, sensors, software and algorithms contribute greatly to the collection, processing and presentation of cultural heritage information as well as its multi-resolution 3D representation. Bakirman et al. (2020) provided a very low-cost solution for cultural heritage documentation using an ultra-light drone to produce 3D point cloud and orthoimage. Digitization of cultural heritage buildings is now a common process, enabling long-term archiving, easy sharing and digital presentation for research and dissemination to the general public.

However, the integrated and multidisciplinary approach is strategic to best represent the cultural property under study. The use of wireless sensors integrated with optical and infrared cameras, enables the production of multispectral and hyperspectral images by improving the construction monitoring system. Shao et al. (2019) studied how to combine two acquisition techniques, based on laser scanning, to acquire detailed 3D models of large physical objects. More specifically, TLS, which provides millimeter resolution with a wide field of view, is combined with Structured Light Scanner (SLS) which provides sub-millimeter resolution with a limited field of view.

The inclusion of Terrestrial Laser Scanning data within the BIM models constitutes the Scan-to-BIM approach, which is not yet sufficiently explored for archaeology (Moyano et al., 2020; Pepe et al., 2021). Galanakis et al. (2023) studied the latest Machine Learning (ML) and Deep Learning (DL) algorithms for large-scale class recognition, but without recognizing small objects. This problem can be remedied by a method that integrates TLS, UAV and AI, which is currently being tested in the study of geomechanical stability at marble quarries in Carrara, Italy (Careddu et al., 2023). The accuracy of the images, processed with artificial intelligence-based algorithms, has reached hundredths of a millimeter.

The Regional Government of Sardinia has recently approved the allocation of fundings for restoration and safety-consolidation intervention of the nuragic complex Sa Jua, in the municipality of Aidomaggiore (western Sardinia, Italy). The present work is part of the preparatory stages to obtain preliminary and necessary information for the elaboration of the project drawings.

2. Geo-archaeologic framework

Aidomaggiore is located in the central area of the basalt plateau of Abbasanta in Sardinia (Fig. 1). The town is one of the Sardinian municipalities with the highest concentration of surveyed archaeological sites: 8 domus de janas, 7 dolmens, 3 allées converte, 57 tombs of the giants, 63 nuraghi, 5 nuragic villages, 6 nuragic wells, 2 nuragic springs, 8 villages of the historic period, 9 betili, 39 tombstones. Most of them are strategically placed: at the edge of the plateau and at the points of best view of their own territory and neighboring areas (Depalmas, 1998; Depalmas and Vidili, 2006).

2.1. Description of the archaeological site Nuraghe Sa Jua

The *Nuraghe Sa Jua* (Fig. 1g) is located about 400 m from the urban center of Aidomaggiore (Figs. from 1a to 1f), and it is positioned on the

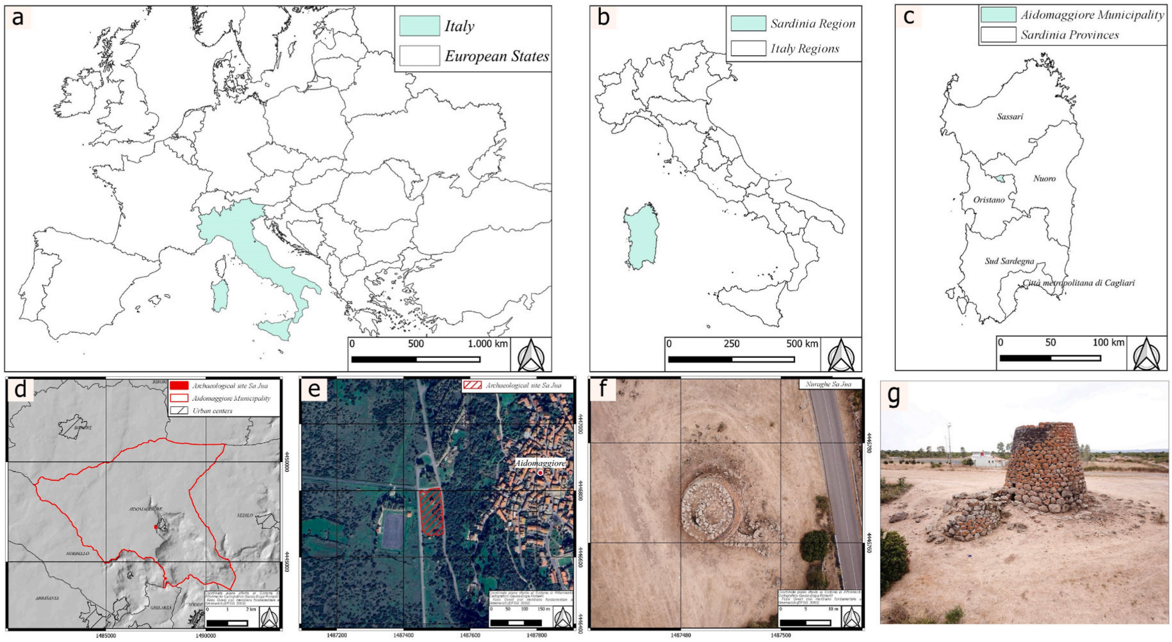

Fig. 1. Geographical localization of Aidomaggiore Municipality and Nuraghe Sa Jua: (a) Italy; (b) Sardinia Region; (c) Aidomaggiore municipal territory; (d) and (e) location of archaeological area Nuraghe Sa Jua; (f) zenith view Nuraghe Sa Jua; (g) view of Nuraghe Sa Jua from N-E.

edge of the plateau at an altitude of 321 m above the sea level. It is a complex *nuraghe* with frontal addition, built with basalt blocks, a stone material that was used from prehistory to the present day (Careddu and Grillo, 2019). The complex *nuraghe* with a frontal addition often represents the evolution from a single-tower *nuraghe*, where a circular building was added to the main tower at a later time, and connected to the original tower by two enclosing curtain walls comprising a courtyard, that was sometimes equipped with a well (Lilliu, 1962; Moravetti et al., 2014). However, it should be noted that not all of the complex *nuraghi* are a result of a previously simple one (Foddai, 2014).

Regarding the construction technique, the nuraghe was built using a mixed technique: polygonal in the lower part of the tower, predominantly in rows in the upper part (Moravetti et al., 2014). There are numerous bibliographical sources pertaining to the monument (Casalis and Angius, 1845; Depalmas, 1998; Taramelli, 1935; R.A.S., 2013).

The main body of the monument consists of a tower which was accessible through a lintelled entrance. In the corridor behind the entrance, after about 2.50 m, on the right, there opens a wall niches, and on the front left, a spiralling-twenty-step staircase (Fig. S1f, Supplementary material), inside the wall mass, which would take to the upper floor. At the top of the monument, a few rows which constitute a circular room (approximately 3.60 m in diameter) are still visible.

On the lower floor, the entrance corridor (length 5.25 m) with projecting walls and a stepped ceiling, leads to the main circular room (approximately 5.20 × 5.00 m) with three wall niches of ogival and trapezoidal section (the one in line with the entrance) arranged in a cross-shaped pattern and about 1.60 m deep. The monument was built with large and medium-sized stones arranged in fairly regular rows towards the top. The maximum height of the main tower is about 11 m, the minimum is 6.50 m, with a height of about 9.60 m at the entrance. A slightly curvilinear wall connects the main tower to the added tower, now without a roof and cluttered with debris from the collapse (5.90 × 7.50 m), with a lintelled trapezoidal entrance (Fig. S1, Supplementary materials). The courtyard in front of it is small (3.40 m × 1.50 m) and it is accessible from the N-E, through a 0.70 m wide opening. The archaeological area extends for about 100 m in radius; near the *nuraghe*, other structures, most likely the *huts* of the village (Depalmas, 1998), can be seen.

2.2. Structural analysis of the monument

The nuraghe is in a fairly good state of conservation: the thòlos of the main tower is perfectly intact. However, the outer wall face in the N-E side, shows criticalities (Fig. 2): the misalignment of the rows may have been caused by the vibrations generated by the resurfacing works of the adjacent access road to Aidomaggiore. On the S-W side, the wall face shows a misalignment of the rows at the stairwell; the cause could be blamed to the presence of roots that wedged into the wall face and caused the wall ashlars to weaken and disconnect, or perhaps occurred during the construction of the nuraghe itself (Fig. S2, Supplementary materials).

3. Materials and methods

The workplan has been divided into the following six steps, as shown in Fig. 3.

1. Initial survey

Fig. 2. Nuraghe Sa Jua, criticality area at the stairwell.

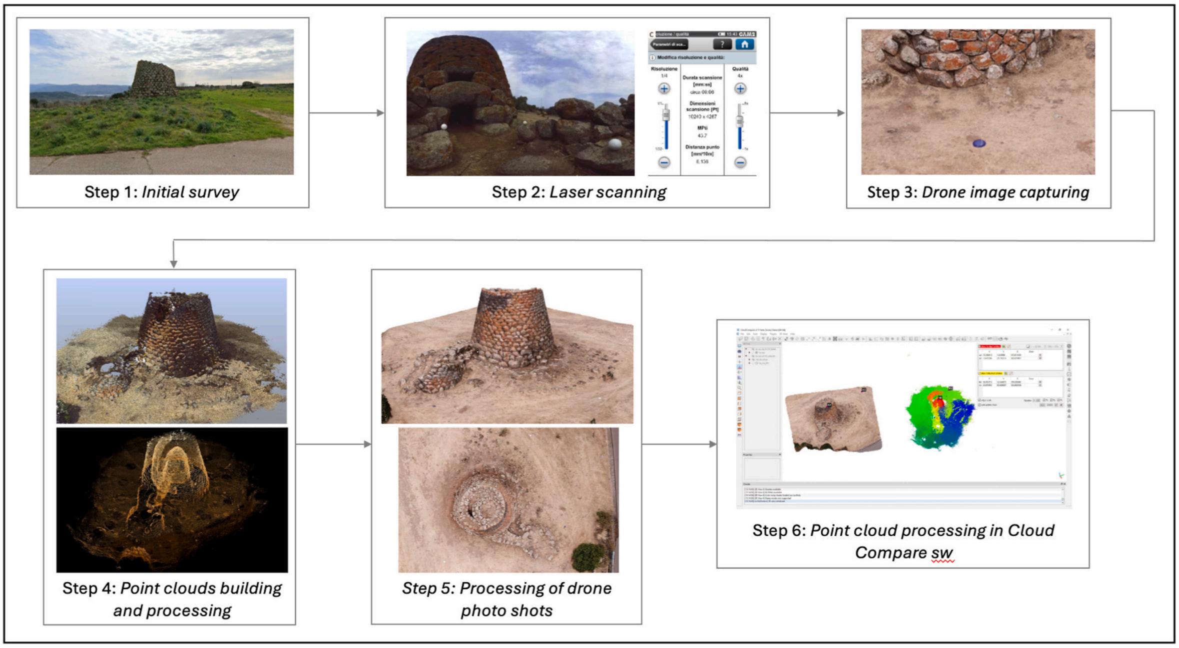

Fig. 3. Workplan.

2. Laser-scanning
3. Drone image capturing
4. Point clouds building and processing
5. Processing of drone photo shots
6. Point cloud processing in Cloud Compare sw

The first step began with the survey of the site, whose objective was to identify the stations and assess the duration of the work time. At this stage, it was necessary to apply for permits, to gain access to the archaeological property.

In the second phase, the targets to be used for referencing were placed. Then, the station locations were identified and the quality and resolution parameters were chosen. The scans were then acquired and saved.

During the third step, the targets for orthorectification of the images were positioned. The drone was guided manually with a set up of 2D processing and of the camera tilt control for the 3D model.

In the fourth step, registration of the scans, the point cloud was constructed; it was then exported and processed in the CAD environment for the production of 2D graphics (plans, fronts, and sections).

During the fifth step, photographic shots from the drone were processed, from which a dense cloud, mesh, texture, 3D model and PDF model export were derived.

In the last step, the point clouds obtained by the laser scanner and the dense cloud from photogrammetry were imported to the open source software *CloudCompare* to align and scale the dense cloud derived from photogrammetry to the point cloud derived from the laser scanner. Finally, the overlap between the point clouds was checked.

3.1. Laser scanner survey

Much of the studies carried out in Sardinia have benefitted from the use of the open source and commercial softwares for the documentation of prehistoric monuments (Fallavollita et al., 2013), prehistoric funerary hypogea (Marcialis, 2015) or for the survey of nuraghi (Lai and Sordini, 2014).

Planning operations is important during the laser scanner surveying. The whole process of choosing stations, their set-up, the positioning of targets and the choice of parameters such as quality and resolution, requires special care so as to facilitate the processing and docking of individual scans in such a way as to obtain an overall point cloud that can entirely cover the object to be surveyed, mitigating the areas from shadow or occlusion as much as possible (Marcialis, 2015).

Integrating drone photogrammetry into the surveying phase offers numerous advantages: the possibility of acquiring high-quality images with a resolution is visibly superior to the point cloud if obtained with TLS; it is also possible to eliminate shadow areas that form at the highest points of the monument, and especially on the wall interstices, when measurements are taken from terrestrial instruments with too high incidence angles (TLS positioned on a tripod); moreover, the drone facilitates the overcoming of the above-mentioned problem because it is possible to acquire images from different viewpoints, and with different inclinations thanks to its wide range of motion.

The *Nuraghe Sa Jua* presents a complex, irregular geometry which is characterized by different spaces (external, internal: entrance corridor, tholos chamber, *wall niches*, staircase leading to the upper floor) that are situated on different levels albeit interconnected. The architectural complexity of the monument required careful planning of the stations, assessing issues regarding the alignment of the scans; the survey was carried out starting from the external part, then moving to the internal part, and finally proceeding through the staircase opening.

The used TLS is a CAM2 Focus3D MS120 that was provided by FARO Technologies Inc. which is phase-different, fast and compact; 32 scans (21 external and 11 internal) were carried out according to resolutions varying between ¼ and ½ of the maximum resolution (average scan step distance: 3 mm at 10 m), for an average duration of each of 15 min, including the time needed to obtain the color datum. Fig. 4 shows the 360-degree panoramic laser scanner views of the thòlos inner chamber (see also Fig. S3, Supplementary materials).

In order to record the scans correctly and allow the software to have accurate docking points, white-colored spherical polystyrene targets were used outside and inside the structure at different elevations and in locations visible from multiple stations; the choice of white to color the targets works particularly well in the interior environments of the structure, where natural lighting is almost absent, since this color is easily detectable from the grayscale images, which are used to dock the scans during registration.

Pre-alignment and registration of scans were performed with FARO

Fig. 4. Nuraghe Sa Jua. The survey campaign, 360° panoramic view from laser scanner of the thòlos inner chamber.

Scene 5.1 software. The export of the point cloud in.rcp format, which is compatible with the most common CAD applications, was carried out with SCENE LT software. In the CAD environment, the point cloud was processed to obtain floor plans, fronts, and sections. The creation of external and internal scans helped to highlight the thickness of the wall face and the different environments of the structure as shown in Fig. 5 (see also Fig. S4, Supplementary materials).

3.2. Plans, fronts, and sections

The ability to integrate point clouds, meshes, orthophotos into the AutoCAD environment offered the chance to produce complete and easily shared graphical tables. Once the point cloud was imported, it could be processed to draw plans, perspective views and sections of the three-dimensional model as shown in Figs. 6 and 7.

Through making multiple sections, along predefined directions, it is possible to highlight the wall thicknesses of the wall face at the lintel entrance and the front wall (Fig. 7a and b), as well as highlight the variations in wall thickness at the stairwell (Fig. 7c and d).

3.3. Drone surveying

Aerophotogrammetric surveys were performed with a DJI Mavic Pro. The drone is equipped with 5 optical sensors and a 4K camera stabilized by a 3-axis mechanical gimbal and 12-megapixel camera with Adobe DNG RAW support. Featuring a flight time of 27 min (at a constant 25 km/h and no wind) and a stationary flight time of 24 min (no wind). Drone specifications are summarized in Table S1 (Supplementary materials).

Manual flight was preferred at this stage; in fact, for this type of structure, it allows manual setting of all parameters necessary for proper acquisition of the photographic shots. The time required for the realization of the photographic shots was about 30′, therefore relatively quick and easy. The flight was performed by realizing a two-dimensional zenith grid for subsequent 2D processing; through manual control of the camera tilt, photographic shots were taken at different inclinations for subsequent processing of the 3D model.

Fig. 5. 3D point cloud obtained with SCENE 5.1 and processed CAD environment, detail of the inner chamber, stairwell and thickness of the wall face.

Photographic shots were taken at different elevations (20-10-5 m) in order to obtain wide images for orthophotos and detail images for 3D model making. The photographic shots were taken with an overlap of about 60 % and a sidelap of about 50 %. To preserve the scale of the model, four colored circular targets were placed on the ground at a distance of 20 m from each other.

Integrating the TLS survey with photogrammetric survey has resulted in more reliable reference points (both markers and directly on the wall structure) and obtaining an alignment of the models starting from the high precision of the point cloud derived from TLS.

3.4. Orthophoto and 3D model

Once the photographic shots have been acquired, polygonal and structured models are processed through a fully automated workflow system, metrically corrected and high-resolution orthophotos, DSM, shown in Fig. 8.

Agisoft Metashape is a fundamental tool for creating detailed 3D models from aerial or terrestrial images. It is used for the documentation and virtual reconstruction of archaeological sites, facilitating the analysis and preservation of cultural heritage.

The processing of photographic shots follows the sequence of the photos and it turns them into a complete set of three-dimensional and geospatial products.

During the Dense Cloud processing phase, the images are aligned and processed to identify and connect by corresponding points in 3D space. This dense representation of the surface is the basis for all subsequent products (Fig. 8a). Next, the Wireframe Model is generated, therefore the Dense Cloud points are connected to form a triangular, three-dimensional basic mesh. This model provides a visual guide to the shape of the object (Fig. 8b)

The Wireframe Model then becomes the starting point for the Solid Model. The Wireframe is filled with solid surfaces, by using triangulation algorithms, and creating a complete and detailed three-dimensional model of the object (Fig. 8c).

Once the Solid Model is ready, the Texture Model is created. The original images are projected onto the surface of the solid model, applying textures and colors to make it more realistic and detailed (Fig. 8d). In parallel, the Orthophoto is processed, with the orthorectified images combined to produce a geometrically correct aerial image. This photographic representation of the area is useful for visualization and spatial analysis (Fig. 8e).

Finally, we complete the process with the creation of the Digital Surface Model (DSM) (Fig. 8f). Starting from the Dense Cloud, a digital model of the terrain elevation and structures present is generated. This DSM is essential for the creation of detailed topographic maps and geospatial analysis.

In short, a series of three-dimensional and geospatial products is produced starting from individual drone photographs. The outcome provides a full range of data for analysis and visualization of the archaeological monument.

3.5. Use of open-source software

CloudCompare is a free software that allows to visualize and process point clouds and meshes in the most popular formats and on different platforms (Windows, IOS, Linux) with simple operations such as: open files in different formats and inspect the three-dimensional point cloud by rotating it in the three axes of space; draw lines and polylines on the three-dimensional model to highlight important aspects or parts; measure distances and surfaces to estimate volumes and interventions; query point coordinates. This application allows complex operations such as

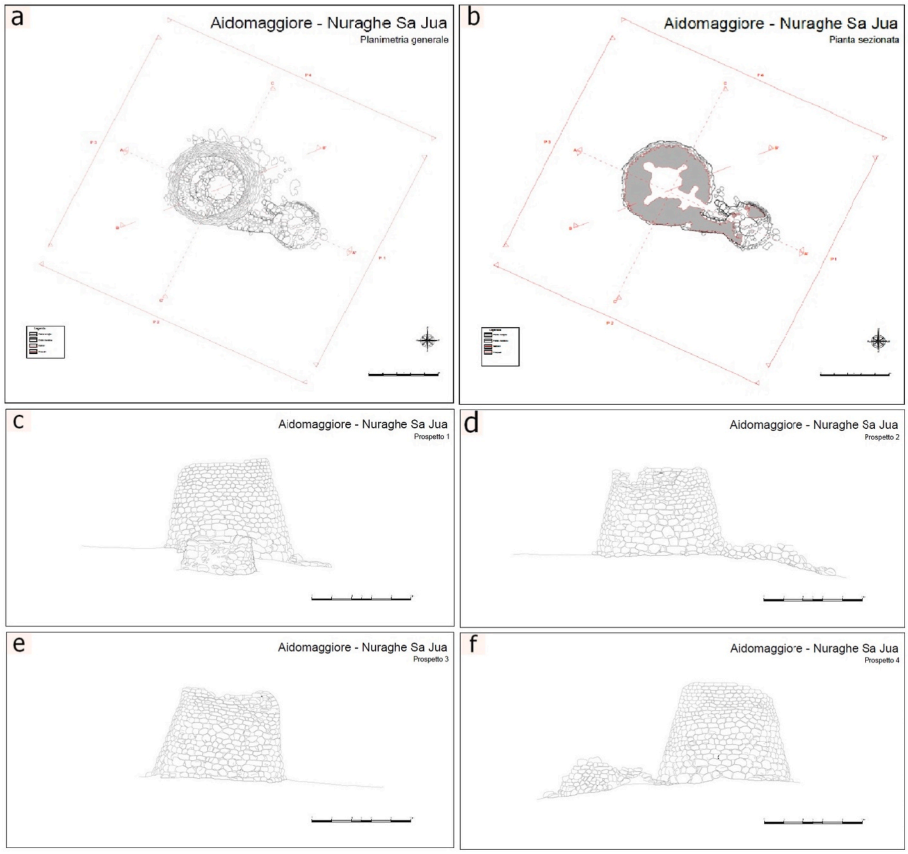

Fig. 6. Nuraghe Sa Jua: a) general plan; b) sectioned floor plan; c) front 1-view S-E; d) front 2-view S-W; e) front 3-view N-W; f) front 4-view N-E.

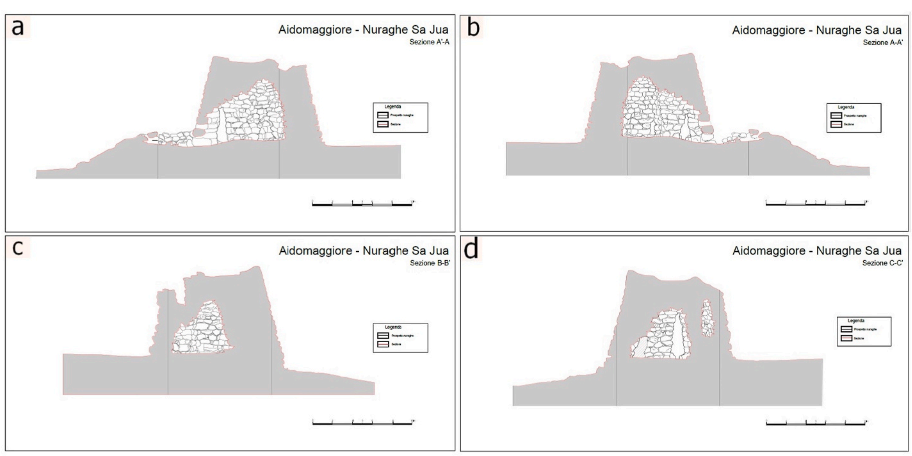

Fig. 7. Nuraghe Sa Jua. a) Section A-A'; b) section A′-A; c) section B-B'; d) section C-C'.

extracting cross-sections of rock walls and exporting them to CAD environment to design e.g. safety interventions, aligning point clouds from different surveys (e.g. laser scanner and drone), scaling point clouds with respect to a reference cloud, noise reduction, fusion etc.

Point cloud processing is based on an *octree* structure that allows high performance when performing this type of computation (Girardeau Montaut, 2019). In the post-processing work, *CloudCompare* was used to obtain a unique model by merging the point cloud from the laser scanner with the dense cloud from the photogrammetric processing of the drone-sensed images and check for any differences in the processing of the same. The individual point clouds, once imported into the software, were aligned; this procedure was possible due to the recognition of common points (at least three) among the point clouds (Fig. 9).

It should be emphasized that there cannot be a perfect overlap between the two models; however, the overlap showed a good level of accuracy between the two clouds, with a deviation of less than a centimeter and thus highlighting the correctness in data acquisition.

4. Results and discussion

The work carried out at the Sa Jua Nuraghe highlighted a number of benefits from the joint and integrated use of laser scanning and drone photogrammetry: the pinpoint accuracy of the laser scanner combined with the aerial coverage and rapidity of acquisition of drone

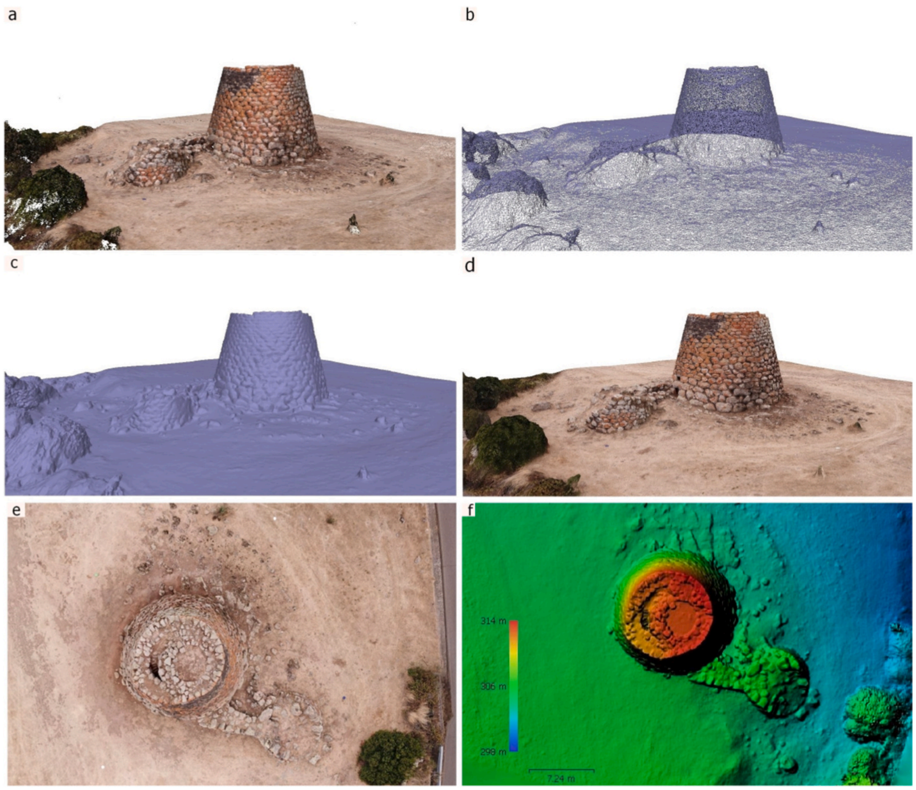

Fig. 8. Development processing snapshots from drone: a) dense cloud; b) wireframe model; c) solid model; d) textured model; e) ortofoto; f) DSM.

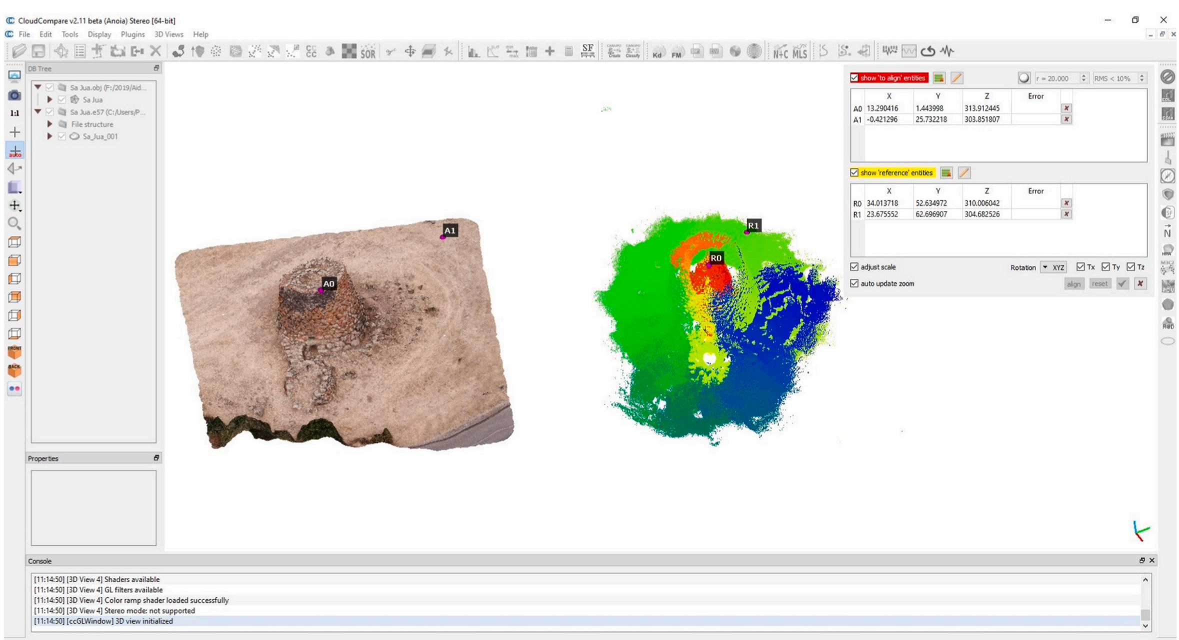

Fig. 9. Aligning the two point clouds on Cloud Compare sw.

photogrammetry generated a complementary data set and a wide range of benefits that contributed significantly to the understanding and preservation of the archaeological monument.

In the field of architectural surveying in general, and archaeological surveying in particular, the laser scanner is an indispensable element. One of the main virtues of this technology is its ability to capture intricate details of structures with pinpoint accuracy. This allows engineers and scholars to obtain an accurate and detailed three-dimensional view of sites, by providing a solid basis for subsequent analysis and documentation.

In addition, laser scanning is particularly effective in creating 3D models of structures, and it offers a digital representation that faithfully preserves architectural features. Such virtual representation is invaluable for better understanding of the time-related evolution of structures. An additional advantage of the laser scanner is its ability to operate even in adverse environmental conditions; compared to other methods, the laser scanner is less affected by external factors such as lighting and adverse weather conditions, ensuring reliable results regardless of context.

Alongside these many positive aspects, however, it is worth noting some aspects of laser scanning surveying that still present critical issues, especially related to the cost of equipment (both instrumentation and software needed to process the large amount of data), the necessary skills in the use of processing software, and the difficulties in exporting and using models in standard CAD and graphics applications.

On the contrary, the introduction of digital photogrammetry techniques (SFM) has allowed for precise 3D surveys with good image quality, with greater ease in learning the survey techniques and at affordable costs, in terms of the necessary equipment (drones and terrestrial cameras) as well as for the software, whether commercial or open-source.

The introduction of drone photogrammetry has further expanded the possibilities for archaeological investigation; drones provide an aerial perspective that reveals the totality of a site, allowing panoramic views and extensive coverage. This is particularly advantageous for archaeological sites that are large or difficult to access from the ground. Drone photogrammetry allows high-resolution images to be captured from different angles, thus creating a set of photographic data that can later be processed to generate detailed 3D models. These models, which are obtained by combining photographs taken from different perspectives, provide for a fully immersive and interactive visualization of the site.

The images acquired through photogrammetric techniques allow for the creation of models and orthophotos that are metrically correct and georeferenced, with higher quality and resolution compared to the point clouds obtained with TLS. The speed of data acquisition is another positive aspect of both techniques: the operator who has both at their disposal must be prepared to choose the most advantageous one each time, or at least know how to combine them in the most appropriate way for the case at hand.

Whereas traditional methods required considerable time to cover large areas, drones can complete the survey in a short amount of time, allowing for greater efficiency in field operations. The versatility of drone photogrammetry is also evident in its ability to capture topographical details and document changes in the surrounding landscape over time. This is of particular importance for archaeological sites which are threatened by erosion or other environmental-related dynamics.

The integration of these two technologies made it possible to obtain a comprehensive and detailed overview of the monument. The possibility of superimposing and comparing the data obtained from both methods facilitated the interpretation of the information acquired and facilitated the task of the architect designing the interventions, the Scientific Management and the contractor carrying out the works. The architect-designer needs to accomplish a global reading of the structure by providing scaled plans, fronts and sections to scale. The work needs to be documented by highly accurate graphic drawings and a detailed knowledge and in depth appreciation of the monument by providing features and particularities (e.g. alignments, diversity of wall thicknesses, solutions of continuity, variations, etc.) that might otherwise go unnoticed.

The design drawings, derived from the survey, provide for illustrative schematic plans of the different structural geometries (inner wall face of the thòlos, stairwell, outer wall face); with the support of the photographic survey, these drawings allow to retrace or at least hypothesize the different construction phases and their mutual interconnections (Cappai, 2003). The scanning survey ensures the completeness and detail of this information.

In this specific case, a nuraghe of the frontal addition type was analyzed. Thanks to the analysis of the models and the produced documents, it is already possible to hypothesize the sequence of the wall units in the construction phases. At least two residual rows of the curtain wall connecting the main tower to the secondary one and delimiting a small open space are visible on the southern side. From the analysis of the USM (Stratigraphic Wall Units), it emerges that the curtain wall is not connected to the masonry of the central tower but is attached to it (Fig. 10); at this point, it is impossible to hypothesize, in the absence of stratigraphic data, whether the frontal addition structure is the result of an initial project or a subsequent modification to meet changing needs. Only the continuation of stratigraphic investigations will allow archaeologists to fully understand all the construction and use phases of the nuraghe.

The in-depth analysis also allows the architect-designer to identify constructive features of the monument, by obtaining a quick and schematic reading of the object of study and quickly assess data in order to identify the different phases of intervention in a timely manner. This may result in the removal of any misaligned masonry ashlars, the removal of precarious parts, the relocation of the masonry ashlars in their correct original position and thus ultimately calculate the costs and time of intervention, within a correct and detailed estimated metric bill.

The 3D model of the cloud, which derives from the laser scanner, was extrapolated in a CAD environment in order to produce plans, fronts and sections. The possibility of transparently superimposing the reliefs of the exterior and interior of the structure has further allowed the researchers to understand the different phases of construction of the structure, i.e. to evaluate whether the different buildings, internal thòlos, stairwell and external wall facing they were created at different times or if they were conceived, designed and created in a unitary manner. The company carrying out the works has at its disposal precise, correct and schematic design documents, detailed intervention phases to be followed meticulously, avoiding intervening in an arbitrary manner through processes that could compromise the static nature of the wall system, causing risk situations for the workers.

Table 1 lists a general overview of the strengths and weaknesses between laser scanning and drone photogrammetry in archaeological contexts, highlighting factors relevant to artefact conservation and the specific needs of archaeological surveying.

5. Conclusions

The work carried out at the *Nuraghe Sa Jua* highlighted the benefits of the integrated use of laser scanners and drone photogrammetry. The laser scanner offers very high detail accuracy, allowing for the creation of detailed and digital three-dimensional models, even in adverse environmental conditions. Drone photogrammetry, on the other hand, provides complete aerial coverage of the archaeological site, producing high-resolution images useful for creating detailed 3D models and panoramas of sites, even very extensive ones, difficult to obtain from the ground (Marcialis, 2023). The combination of these technologies has allowed for a comprehensive and detailed view of the monument, facilitating the interpretation of information and the planning of conservation interventions. However, the use of the laser scanner presents some critical issues, such as the high costs of the equipment and the skills needed to process the data.

Digital photogrammetry, on the other hand, is more accessible and offers precise and good-quality three-dimensional surveys at reduced costs, using drones and terrestrial cameras. Additionally, the speed of

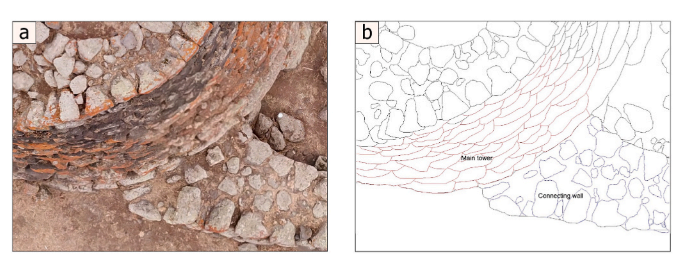

Fig. 10. – Analysis of wall stratigraphic units: a) orthophoto excerpt ((from drone); b) CAD characterization excerpt (from TLS 3D point cloud).

Table 1
Strengths and weaknesses of the integrated survey system used.

Criteria	Laser scanner	Photogrammetry with drone
Preservation of artifacts	Non-invasive, minimizes physical contact with artifacts	Non-invasive, avoids direct contact with archaeological sites
Accuracy	High precision, especially at short and medium range. High level of detail and precision in capturing fine details	Accuracy can vary, generally lower than that of laser scanner
Resolution	Point clouds have high resolution	Resolution depends on camera quality and altitude
Flexibility	Suitable for capturing intricate details of artifacts and structures	Versatile, capable of efficiently covering large archaeological sites
Site accessibility	Limited mobility in confined or difficult to access spaces	It can reach inaccessible or hard-to-reach areas, especially vertical structures
Data collection speed	Slower data collection process, especially for complex monuments	Fast data acquisition, suitable for large-scale surveys
Data volume	It can generate a large volume of data for large or particularly complex sites	It produces a manageable amount of data, suitable for regular monitoring
Initial setup time	Setup and calibration can take a long time	Fast deployment and setup, allowing for rapid data collection
Dependence on weather conditions	Little affected by adverse weather conditions	Sensitive to weather conditions, which affect the reliability of data collection
Post-processing complexity	Requires sophisticated software for data processing	Easier data processing with specialized photogrammetry software
Economic considerations	High costs for equipment and operations	Generally economical equipment and operations
Cultural impact	May require permission and more careful cultural considerations	Less invasive, potentially more acceptable from a cultural point of view
Environmental impact	Minimal environmental impact	Low environmental impact, but noise (however low) and privacy problems could arise

data acquisition is a significant advantage for both techniques, allowing for greater efficiency in field operations. The integration of these technologies has resulted in a complete overview of the monument and has facilitated the work of architects and experts in planning interventions. The overlay of the acquired data has allowed for a better understanding of the construction phases of the structure and to formulate hypotheses about the different construction phases of the nuraghe.

At the current state of research, we are not able to understand whether the complex nuraghe is the result of a single initial project and therefore if it should be regarded as a single construction phase. However, following the analysis of emerging USMs, it appears that the curtain wall leans against the central tower. Only the continuation of the excavations will enable archaeologists to gain a deeper understanding of the construction phases and the employment of the nuraghe.

In summary, the combined use of laser scanners and drone photogrammetry has significantly contributed to the understanding and conservation of the archaeological monument whilst providing a solid basis for analysis, documentation, and planning of future interventions. The collected data are easily shareable, accessible, and archivable for future use, both from a documentary point of view and as a starting point for future conservation projects or structural monitoring and stratigraphic investigation activities. Moreover, high-quality data processed can be easily shared and consulted by public administration (PA) officers.

The advantages of non-contact three-dimensional survey techniques, whether laser scanning or photogrammetric, allow for clear advantages in qualitative terms as well as in terms of time saving during the survey and processing phases. In the case of archaeological and restoration studies or sites, which is undirectly related to the research world, albeit involving freelancers, companies, and private entities, time is directly linked to costs, and an improvement in this sense can be fundamental for the dissemination of these techniques and can bring significant advantages to all involved parties. Furthermore, remote surveying allows operators to acquire measurements and images in total safety and without the need to directly access points of the structures that could endanger the operator's and the monument's safety.

Lastly, an indirect aspect of the advantages offered by integrated three-dimensional surveying also has an impact on civil society. More specifically, it deals with the objective of the conservation and protection of cultural heritage, which the work of scholars and professionals helps to ensure. Another aspect is related to the possibility of using digital models for the creation of virtual tours or reconstructions, useful both for the promotion of cultural heritage and for tourism and educational purposes, whilst offering the possibility of virtually visiting sites even to people who struggle to or are unable to access them physically.

CRediT authorship contribution statement

Antonio Dessena: Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Paolo Marcialis:** Writing – original draft, Resources, Investigation. **Nicola Careddu:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2025.e00440.

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