Combined 3D survey and Ai techniques for enhancing Fortified Heritage.

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COMBINED 3D SURVEY AND AI TECHNIQUES FOR ENHANCING FORTIFIED HERITAGE

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Abstract *Military heritage is closely linked to the history of human settlements and territories, since in any era, military structures have been a major concern for communities, and are well-known examples of the strong connection between human activities and the natural environment. In this sense, military heritage is included within the broader context of defensive landscapes, constituting a perfect example of the integration between human labour and nature, where tangible and intangible heritage are intrinsically linked.*
The research aims to define the morphology and characterise the context of examples of the vast infrastructure of the Alpine region through military underground structures constructed in reinforced concrete (Opere) in the decades preceding World War II and known as the Vallo Alpino Littorio. The knowledge gathering approach is conducted through metric surveying and 3D modeling using multi-sensor techniques (photogrammetry and laser scanning). The nature of defensive structures to guarantee inviolability makes them difficult to access or completely inaccessible today, and above all to define the relationship with the context which is often wooded or in any case rich in vegetation, AI techniques are useful to support their documentation aimed at enhancements and possibly re-use.

1. INTRODUCTION AND RESEARCH AIM

The digitalisation project of the military heritage in the Stura Valley (Piedmont, Italy), which is the subject of this contribution, addresses a broad range of challenges currently identified for the proper knowledge and conservation of cultural heritage.
First, digitalisation leverages innovative 3D survey technologies based on range and image-based methods to generate accurate and detailed 3D models of spaces, environments, landscapes, and architectural scale complex or buildings under investigation. 3D surveying and modelling, often inspiring or followed by their transformation into cognitive systems that can be navigated and shared within the community of conservation scholars and specialists, is considered the first phase of the knowledge-building process that precedes and constitutes the essential foundation for heritage conservation.
These essential implications of digital information are connected to the evolution of the principles that regulate heritage protection, which broadly include geographic and spatial data, as well as being coordinated with those of a thematic nature linked to the various interdisciplinary approaches to conservation. In the context of this project, these specific issues intersect the dispersed nature of military heritage and its relationship with the Alpine spaces' natural environment.
The concept that knowledge and enhancing heritage helps to recognise the identities of the communities that have expressed it and promote their involvement, has been well-known and widespread since the Faro Convention[1], playing a particularly significant role in the case of military heritage in mountainous areas, which create a truly highly recognisable defensive landscape, based on their integration and coexistence with the natural environment[2].
The Italy-France cross-border project (Cognitio-Fort) aims to enhance this particular landscape and its military "Opere", also through the involvement of the Geomatics research group of the Politecnico di

[1] CONSIGLIO D'EUROPA, *Convenzione di Faro*, 27 ottobre 2005, n. 199.
[2] ICOMOS *Guidelines on Fortifications and Military Heritage*, 2021

Torino of which the authors are part. In particular, the research focuses the heritage consisting in the "Opere" of *Vallo Alpino Littorio* which are mostly made of reinforced concrete and developed in caves[3]. The military structures have been built during the decades preceding the II World War, and, as often highlighted by historians, they are combined with previous fortifications mostly from the nineteenth century and earlier, demonstrating that the defensive efforts, although deployed in different eras and with different construction systems, are influenced by adaptation to the territory morphology[4].
The deployment intensity of the military works on the territory, at different altitudes and with different densities depending on whether they are close to borders and mountain passes, as well as their complexity both in terms of planimetry and structure, is impressive (fig. 1, 2). In this sense, the defensive landscape also represents the intangible values of the human effort required to build the Wall[5], also considering that the workforce was taken away from the sustenance of communities already worn out by the harshness of living in inaccessible places and by subsistence economies.
The aim of the research program is to digitally document this military heritage, so that it can serve as a resource for sustainable tourism development, thus driving social and cultural development, in line with the United Nations' development agenda (SDGs)[6]. The objective of digitalising the *Opere* and their context is multifaceted: to assess their state of conservation and accessibility to determine possible public visits, to raise awareness of them, and to foster those values that define their identity and booster conservation awareness. 3D models also enable virtual visits in cases of particularly difficult accessibility, where the altitude is not suitable for non-specialists or when hiking trails are not accessible to all.
The paper is therefore structured in the introductory paragraph 1.1 to report some functional and historical traits of the defensive system, which was abandoned without practically ever coming into operation; the chapter concerning the investigation methods is structured in two paragraphs, the first (2.1.) dedicated to the geographical distribution of military asset, while 2.2 focuses on the geomatic methods studied and developed to carry out 3D surveys of the cave works, often presenting walled-up openings for safety reasons, which certainly make them places and built structures particularly challenging for measurement systems. Chapter 3 presents some of the conducted applications results, and above all, it is dedicated to analysing the 3D points models through the use of artificial intelligence techniques to classify the point clouds and segment the ground from the vegetation, precisely to more easily evaluate those accessibility characteristics that could give a new life to the structures.

1.1. Defence Heritage, its abandonment and enhancement

The defensive system of western Piedmont, and that of Cuneo valleys in particular, is not just a military infrastructure but is configured as an interconnected system of military defense works and a dense network of roads and routes (essentially mule-tracks), suitable for allowing direct connections without compromising security. From the mid-18th century (War of Austrian Succession) until the decades preceding the Second World War, the Alpine region was the scene of continuous works to strengthen its defences, up until the profound transformations of the construction systems and the use of reinforced concrete due to the appearance during the First World War of new armaments which made the nineteenth-century fortifications absolutely vulnerable[7].
The defensive system of the *Vallo Alpino Littorio* was organised into *caposaldi* deployed along lines of defence with respect to the direction of the presumed enemy penetration, which included *Opere* and cave observation buildings; they were linked to shelters, barracks and reserves for the artillery. This main system was often accompanied by the provision of cable transport systems to move materials and armaments efficiently when the steep climb made transport on the terrain too difficult. Most of these *Opere* were never fully completed according to their design aspirations; furthermore, they were not in

[3] P.G. CORINO, *Valle Stura fortificata: alla riscoperta delle fortificazioni della Valle Stura di Demonte, dal forte di Vinadio alle opere in caverna del vallo alpino*, Borgone di Susa, Melli, 1997.
[4] M.VIGLINO DAVICO, *Fortezze Sulle Alpi, Difese Dei Savoia Nella Valle Stura Di Demonte*. L'Arciere, 1989.
[5] UNESCO 2003, *Convention for the Safeguarding of the Intangible Cultural Heritage*, Paris, October 17th 2003.
[6] References among Geomatics methods and activities and SDGs can be found at: W. XIAO, J. MILLS, G. GUIDI, P. RODRÍGUEZ-GONZÁLVEZ, S. GONIZZI BARSANTI, & D. GONZÁLEZ-AGUILERA, *Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals*. In: ISPRS Journal of Photogrammetry and Remote Sensing, 2018, *142*, 389–406. https://doi.org/10.1016/j.isprsjprs.2018.01.001
[7] P.G. CORINO, *L'opera in caverna del vallo alpino*, Borgone di Susa, 1995.

working order during the Second World War, and then, the 1947 peace treaty of Paris mandated their dismantling. Many assets were not destroyed, but their abandonment certainly made them very vulnerable. The fate of the roads, however, was quite different: they were gradually ceded to the State Property Office of the various municipalities in the valley, the latest of which dates back to the last decade; now the Grana, Maira, and Stura Valley Mountain Communities promoted and engaged in some projects to enhance these itineraries[8].
The Opere and the cave observatories are of greatest interest in this research, since although they are completely abandoned, many of them have collapsed and are in a precarious state of conservation, while in other cases the conditions are favourable enough to allow for their recovery and to make them visitable[9]. In particular, the perspectives for further development of enhancement initiatives are linked to understanding their state of conservation and accessibility. These questions are crucial to planning accurate and targeted applications of modern geomatic surveying technologies, as these underground and difficult-to-access structures, as well as their context, undoubtedly present challenging conditions (Fig. 1).

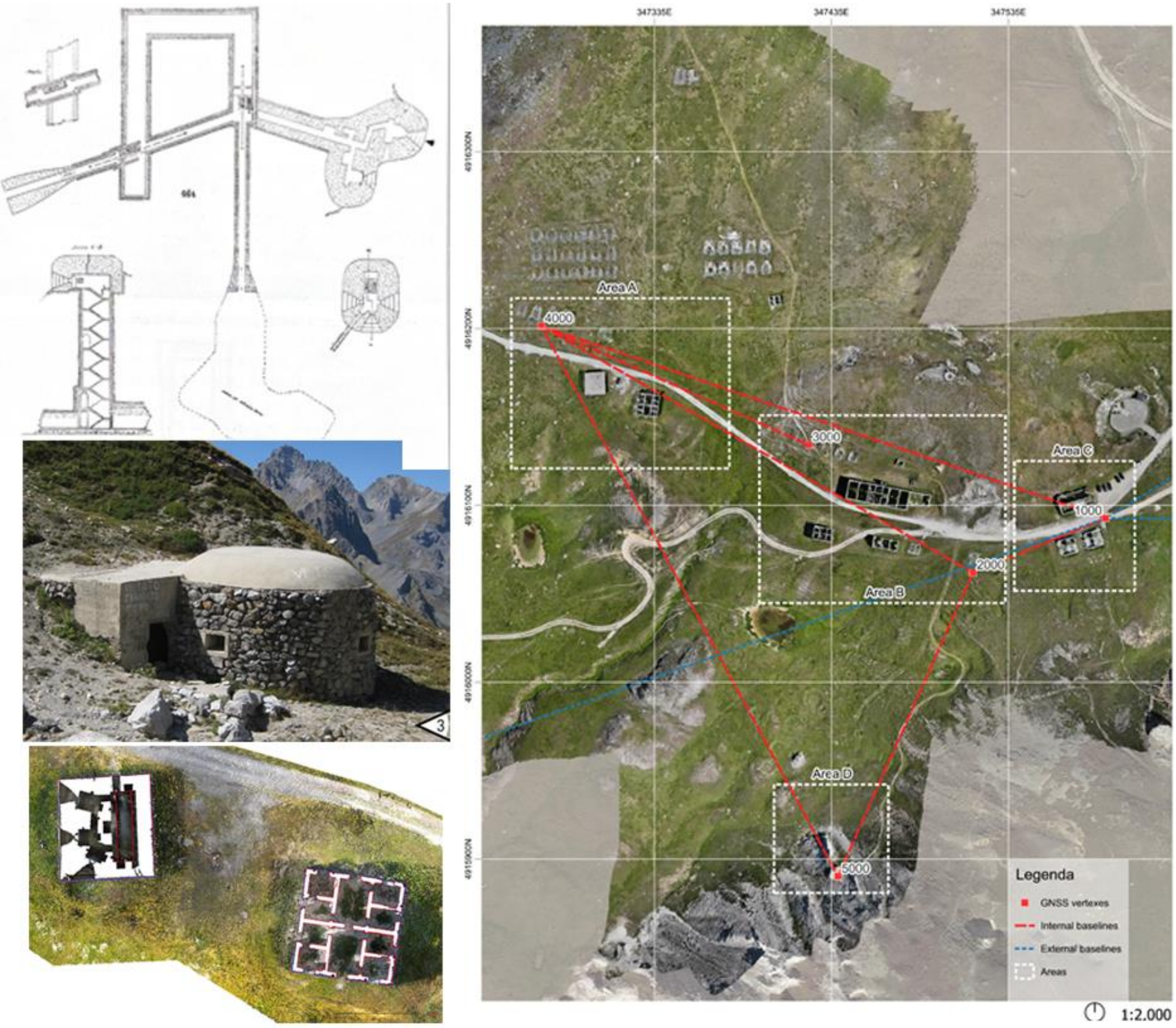


Fig 1. (left column) Project plan of Andonno Opera 9 (Archivio Primo Reparto Infrastrutture – Torino)[10] ; Opera 179, Gardetta pass[11]; Opera 310 (disguised as a 19th-century shelter) and a 19th-century barrack represented by a SLAM based point cloud; (right) the UAV (Unmanned Aerial Vehicle) orthophoto of barracks and Opere at Bandia plateau. The GNSS (Global Positioning System) topographic control network is also represented.

[8] M. BOGLIONE, *Le strade dei cannoni – In pace sui percorsi di guerra*, Blu Edizioni, 2008.
[9] https://www.visitstura.it/cultura-e-arte/attrattive/fortificazioni/moiola-blocco-5/
[10] R. POCKAJ, PG GARRONE, *Le fortificazioni della Valle Gesso: dai ricoveri ottocenteschi al Vallo Alpino: 17 itinerari escursionistici*, Blu, 2013.
[11] V. SANTORO, *"an ògni gir de stra" - Analisi del sistema di fortificazioni e sentieri militari nell'area del Passo della Gardetta (CN). Studio comparativo tra fonti cartografiche storiche e tecnologie innovative di rilievo metrico 3D in ambiente GIS*, tesi di laurea, 2022.

2. INVESTIGATION METHODS

The 3D surveying methods are organised to provide a framework within the environmental context and detailed documentation through a series of processes (orthophotos from drones, DSM/DTM, point clouds and architectural scale drawings) derived from a unique, georeferenced and multi-scale 3D archive. The spatial location, obtained using the GNSS technique, is important for mapping the distribution across the territory and for understanding both its adherence to the morphological characteristics of the alpine orography and for obtaining a clear vision of the diffusion of the military assets and therefore for planning possible enhancement in relation to hiking trails (section 2.1). The architectural scale 3D survey has the role of analysing in detail the functional values of defence works and their coherence with the environmental context, assessing the state of conservation, as well as evaluating the accessibility conditions, which constitute an important key to possible reuse (section 2.2.).

2.1. Mapping framework

The specific aim of planning the defensive system and allowing its controlled construction, as well as enabling a convenient and effective movement of troops and armaments, triggered a vast production of military maps starting from the 18th century, which continued throughout the 19th century and which today allow us to study the phenomenon in its transformations and modernisation[12].

The advent of the first nationwide cartography by the Military Geographic Institute (IGM) between the late 19th and early 20th centuries enabled precise georeferencing of military heritage, which can be managed in geographic information systems using today's codified reference systems. Specifically, regarding the modern defensive system of the *Vallo Alpino Littorio*, the military archive of the Primo Reparto Infrastrutture is a rich source of information regarding the design and construction of military *Opere* and roadworks, including cartographic sources.

A study that has highlighted in great detail how the plurality of GIS analysis tools can be used to analyse and highlight spatial relationships in the geographical reference of military structures layered over the centuries, in relation to mule-tracks and military routes, their dislocation in reference to the orography represented with current regional LiDAR based DTM, as well as visibility analysis from the perspective of examining the environment that can be scrutinized by observatories and *Opere*, as well as the width of the firing angles from the aforementioned assets was carried out as part of a degree thesis[13], which was then also included in an international publication[14].

The contemporary availability of open GIS environments with their webGIS configuration and the use of portable GNSS systems, whose diffusion and low cost make them easy-to-use tools for hikers and mountain lovers, has determined the availability of georeferenced digital information that is useful for both the public and for specific studies (Fig. 2, above)[15].

A very recent project conducted by local administrations and sector associations (ASFAO Associazione Studio Fortificazioni Alpi Occidentali), with public funding (PNRR), is the publication in paper form of an extremely detailed map (1:25000 scale hiking map, Fraternali edition) of the vast phenomenon of the defensive system in the Stura di Demonte valley, which also offers the extension of such Heritage beyond the Alps (Fig. 2, below).

2.2. 3D surveying using integrated image and range-based techniques

The goal of obtaining multi-scale and multi-sensor models of the cave fortifications selected in the Stura and Gesso valleys by the Cognitio FORT project is to document their material and immaterial characteristics, as well as the relationships between the built heritage and the natural environment in which they are located, and obviously, their material consistency and state of conservation.

The generation of the three-dimensional metric surveys, aimed primarily at documenting the overall morphology of the fortified structures and their construction elements, necessarily required a comprehensive and unified approach based on integrated terrestrial laser scanning techniques, both

[12] R. SCONFIENZA, *Archeologia militare d'età moderna in Piemonte. Lo studio della fortificazione campale alpina*, in Archeologia Medievale 2012, n. 13. Also: V. SANTORO, 2022, cited.

[13] V. SANTORO, 2022, cited.

[14] V. SANTORO, G. PATRUCCO, A. SPANÒ, (*Multisource 3D analyses for the detection and documentation of a submerged defensive system: the Vallo Alpino Littorio in the Gardetta Plateau area (CN).* In D. R. FIORINO, E. PILIA, T. TEBA (Eds), Conservation of Architectural Heritage (CAH) Springer International Publishing, 2025.

[15] E. GALLO, *Rappresentazioni e analisi spaziali mediante strumenti GIS per la valorizzazione del Vallo Alpino occidentale in Valle Stura*, tesi di laurea, 2019

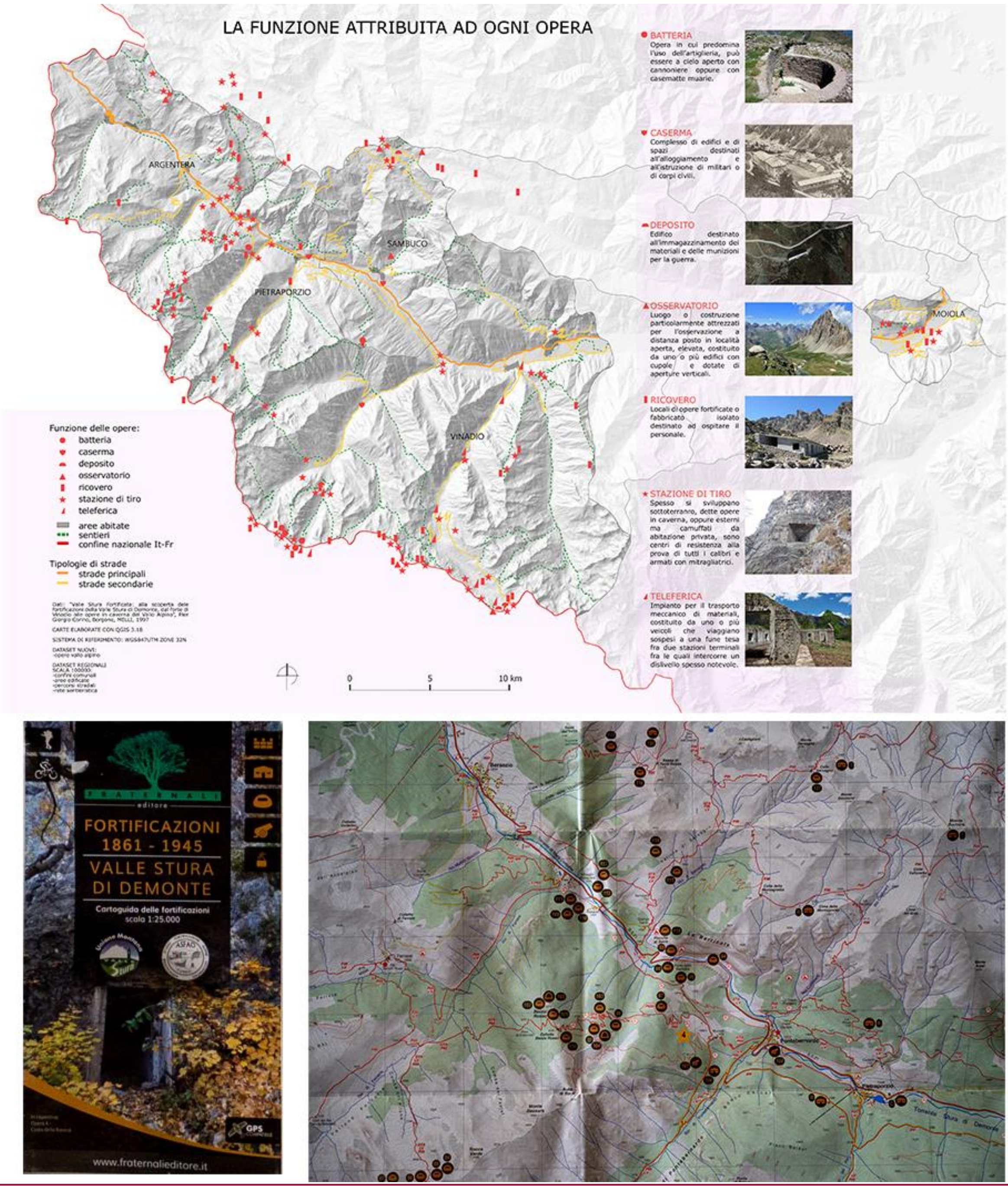


Fig.2. (above) Upper Stura Valley Map showing the extremely dense phenomenon of the *Vallo Alpino Littorio* defence system[16]. (below) A paper map published recently showing the military heritage in the Stura of Demonte Valley.

traditional (*TLS*) and mobile (*SLAM-based*), to connect the external and internal spaces, and high-resolution photogrammetric applications by UAVs (*Unmanned Aerial Vehicles*), commonly known as drones.

The adopted consolidated techniques have the role of defining the general geometric configuration of the built surfaces, both external and especially those excavated internally on steep slopes. The underground spaces, not being able to rely on satellite positioning techniques that do not guarantee indoor signal reception, are addressed using the most recent solution based on a mobile scanning system supported by SLAM (*Simultaneous Localisation and Mapping*) technology. The 3D metric survey project, originating from geomatic techniques, involved the creation of dense and accurate point clouds followed by graphic documents extracted from them, all validated from a metric point of view.

Given the essential geo-location and error propagation check ability that topographic references offer, although the conditions of the natural context are sometimes characterised by thick vegetation (as

[16] E.GALLO 2019, cited.

occurred for the first military asset investigated, Opera 9 of Andonno), and not entirely favourable to the drafting of a network of topographic vertices, we aimed to obtain them through the planning of appropriate schemes of reference points determined through the combined use of GNSS and traditional techniques (total station).
This approach enabled the accurate control of the survey's metric quality. The combined GNSS and traditional technique is crucial for bringing the reference system into the Opere, for the development of the internal 3D survey. This combination is complemented by topographic measurements of control points using traditional topographic techniques to control propagation errors and ensure that the metric results are accurate enough to meet the expected tolerances (within a few millimetres for the vertices coordinates and for the LiDAR clouds registration; a few centimetres for the aerial image blocks orientation and for SLAM-based point cloud). To achieve a similar result, LiDAR and UAV photogrammetry surveys are also used as *ground truth* to register and assign reference to the SLAM clouds; by their nature, they are less dense and accurate in comparison to LiDAR technology, but in the context of cave buildings aim to document the internal spaces with satisfactory accuracy, as mentioned, of the order of a few centimetres.

3. RESULTS AND ANALYSIS

The 3D survey results are typical two- and three-dimensional metric outputs, some examples of which are shown in Fig. 3: georeferenced orthophotos from images acquired by UAVs, 3D models in the form of colored point clouds that combine datasets of LiDAR and SLAM-based clouds using ICP (*Iterative Closest Points*) algorithms and the collimation of control points with known coordinates. The point clouds, at least near the entrances, are validated using deviation maps to ensure that the deviation between clouds is within the predefined limit of a few centimetres. Finally, architectural-scale drawings or, in the future, HBIM (*Heritage Building Information Modelling*) models can be derived from the 3D clouds or from the generation of continuous surfaces (*meshes*).

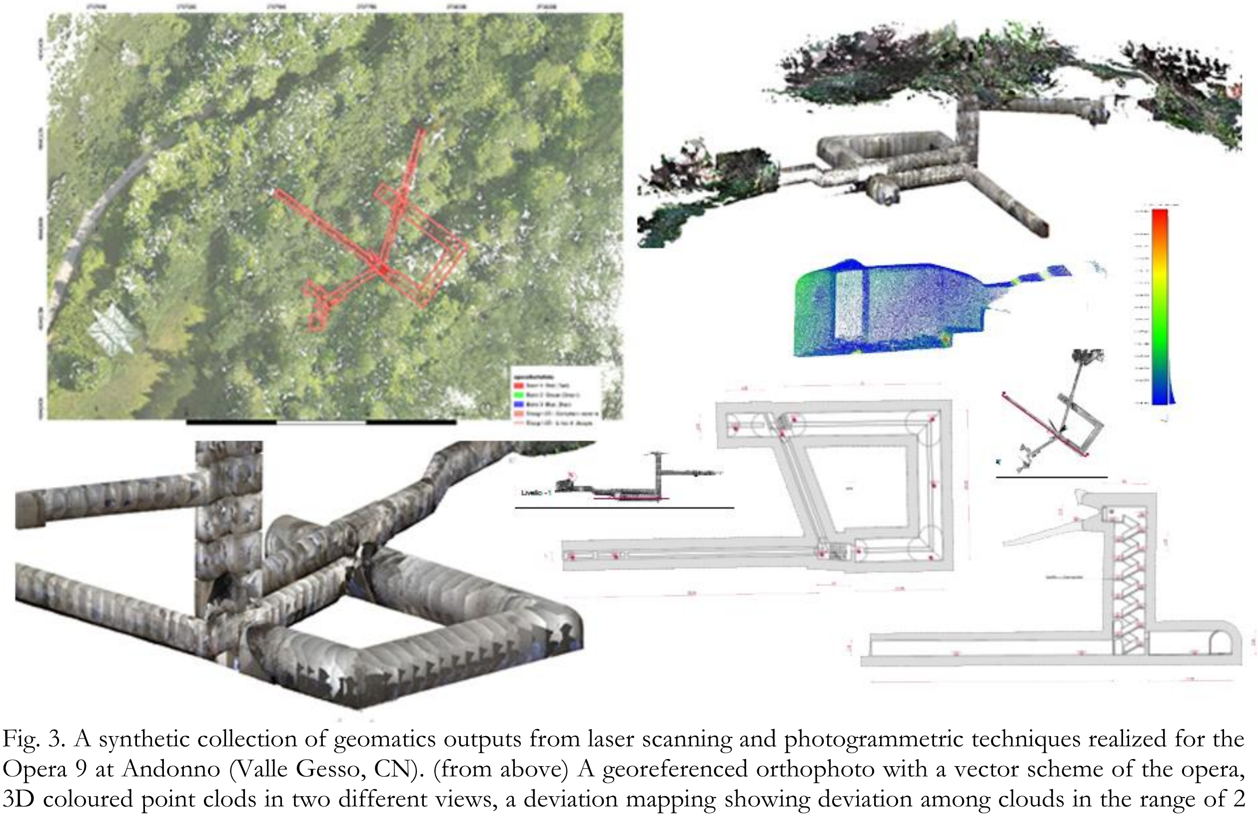


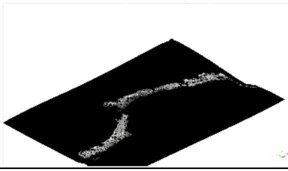
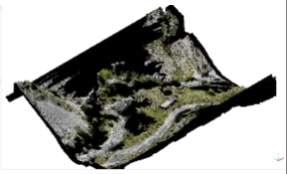
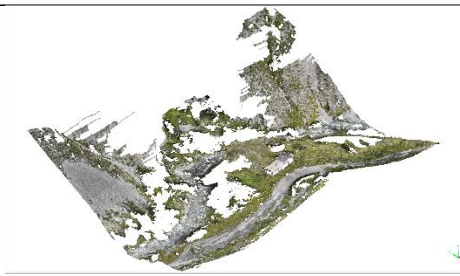
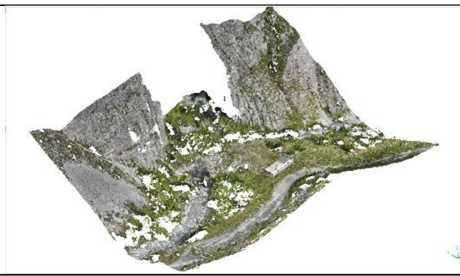
Fig. 3. A synthetic collection of geomatics outputs from laser scanning and photogrammetric techniques realized for the Opera 9 at Andonno (Valle Gesso, CN). (from above) A georeferenced orthophoto with a vector scheme of the opera, 3D coloured point clods in two different views, a deviation mapping showing deviation among clouds in the range of 2 millimetres and 3 centimetres, and sample final dimensioned drawings.

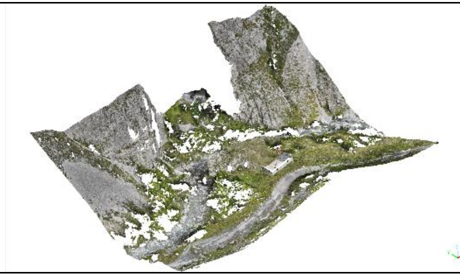
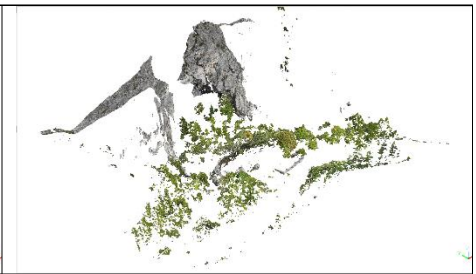
3.1. ML technique for accessibility evaluation (Opera 7 at Barricate – Pietraporzio, CN)

In the context of heritage conservation documentation, the multi-scale and multi-sensor nature of digital models, such as those generated for the defensive system of the *Vallo Alpino Littorio,* is considered the

most suitable condition for preparing a model capable of twinning the real object.
Although current research also proposes the chance of directly using classified point clouds to create the so-called Digital Twin of the object under investigation, the most widely accepted approach in the planned conservation scenario is to adopt the HBIM paradigm, which can make use of *reverse modelling* techniques based on *scan-to-BIM* solutions. One of the most significant contributions of the research also lies in the study of techniques that allow for obtaining parametric models as quickly and with the least possible involvement of human resources. That involves the use of artificial intelligence techniques based on Machine Learning or Deep Learning strategies to classify clouds, i.e., identifying surfaces that correspond to unique technological or architectural elements, automatically and rapidly.
In the case of military heritage, the objective was focused on UAV clouds pertaining to the surveyed sites, and a ML approach was used to classify the clouds, with a particular focus on vegetation. Specifically, a *Random Forest* (RF) algorithm can be used, which is provided by both commercial or open software and leverages a "decision tree" model to generate a series of predictions. In the case of the present research, a pre-trained predictive model embedded in the used photogrammetric software was used to assign each input data item to a specific class based on the greatest probability of belonging to that class. The application concludes with the evaluation of deviations from the manual selection of cloud portions belonging to the *Ground* and *Vegetation* classes. This method is a consolidated strategy used in many application sectors, but it is also appropriate to employ these tools in the heritage sector, which requires effective and rapid approaches.
In the case of Opera 7 at Barricate (Pietraporzio, CN), after 316 images orientation in a standard photogrammetric application (the RMSE of GCP is 1.02 cm while the RMSE of CP is 1.2 cm, which fulfil the demand) a dense point cloud was derived based on depth maps generated from the oriented imaged at their original resolution. The generated point cloud contains 89,441,713 points. Considering the environment of the mountain region (wind's influence on vegetation), the points with confidence lower than 3 was removed, which lead to a result of a clean point cloud with only 51,406,701 points (Fig. 4, above). The CSF (*Cloth Simulation Filter*) algorithm has been a promising option for ground-vegetation classification, as it is possible to observe from the test samples exported as Table 1 shows.

Table 1. Application of different indexes of CSF algorithm to classify the point cloud. The test numbers 3 (Resolution 0.5, Threshold 0,5) and 4 (Resolution 0.2, Threshold 1) are removed from the table due to space limitations.

Cloth setting (parameter)	Ground	Off-ground
Test 01 Resolution 2 Threshold 0.5 		
Test 02 Resolution 0.5 Threshold 0.5 		
Test 05 Resolution 0.05 Threshold 1 		

Test 06 Resolution 0.1 Threshold 1 		

The Fig.4 show the main step of the workflow aiming at registering and obtaining a whole point cloud representing the outdoor and indoor spaces of the Opera 7 at Barricate, merging the UAV cloud and the SLAM-based point clouds acquired inside the underground space.

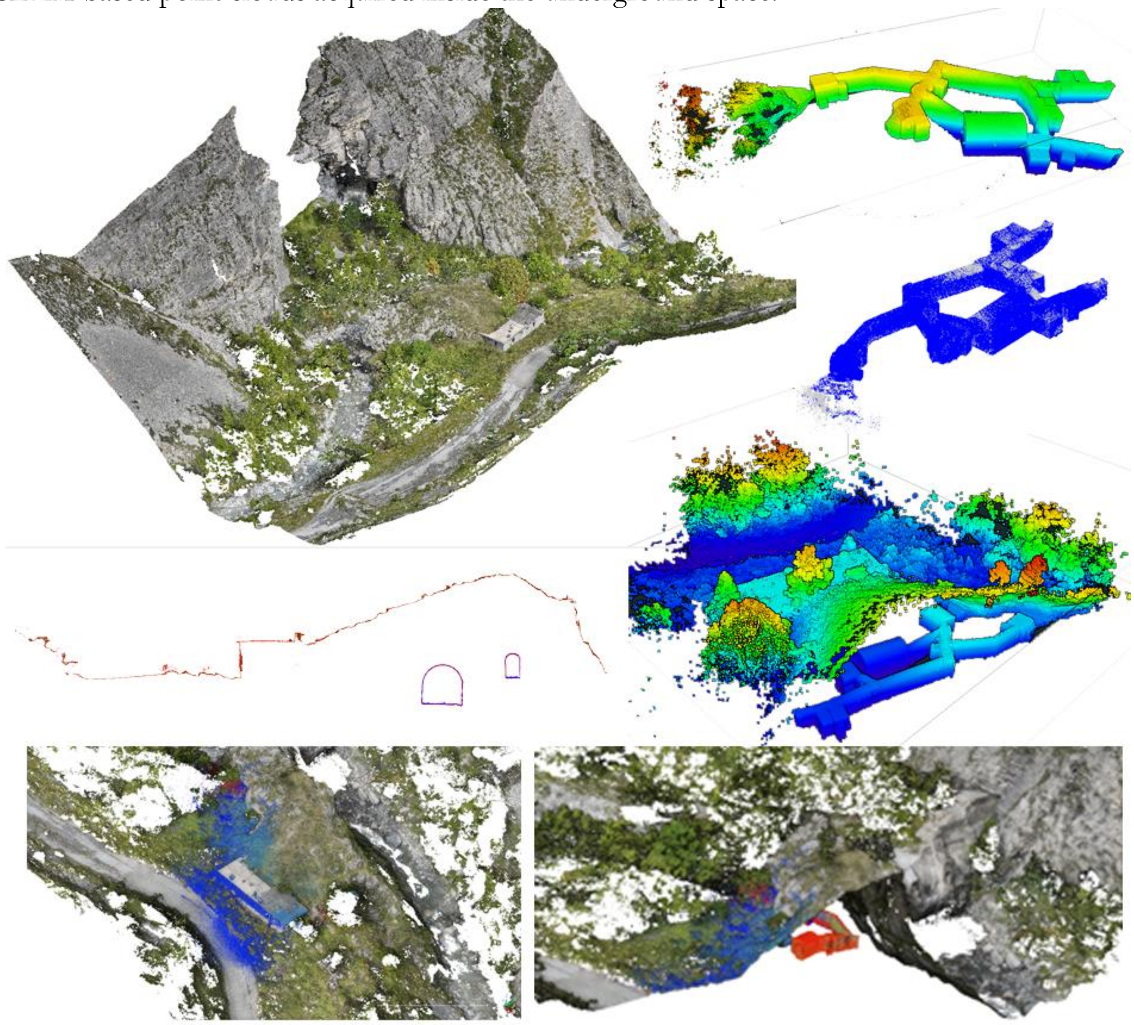


Fig. 4. The whole point cloud from UAV data (above left), and the two SLAM-based clouds acquired in the indoor space (above right). The blue/grey cloud represents the deviation analysis that compares the two clouds, also evaluating the maximum residual error close to 3 cm. The profile section extracted from the merged outdoor and indoor cloud (in the middle), and (below) the merged clouds, are sectioned by a vertical plane to show outdoor and indoor spaces.

4. CONCLUSION

The research aims to highlight the complexity of 3D documentation in the presence of a scattered heritage, which constitutes a landscape worthy of valorisation, such as that of the Vallo Alpino Littorio, presenting assets also located above 2,000 meters above sea level. Although this heritage cannot be exactly equated with a classic industrial heritage, it is interesting to compare this military infrastructure, featuring territorial incredible territorial extension, to the era of the development of the use of reinforced concrete, certainly cast in situ and with significant difficulties in transporting construction materials and establishing construction sites alongside the structures. Given the implementation complexities of such digitization activities, all possible supports, including those deriving from artificial intelligence in the post-production phases of the models, should certainly be explored to make the time and human resources dedicated to producing the 3D documentation products more sustainable.