MULTISPECTRAL UAV DATA ENHANCING THE KNOWLEDGE OF LANDSCAPE HERITAGE

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KEYWORDS: UAV photogrammetry, multispectral imagery, landscape heritage, SLAM-based MMS, spectral indices

ABSTRACT:

Landscape heritage, especially if it does not arouse great public echoes, needs great attention, starting from knowledge and metric documentation processes to which reality-based sensing techniques often contribute significantly. The primary purpose of this work is to reflect on the possibility of identifying submerged built heritages, which are sometimes characterised by precarious safety conditions due to abandonment, through multispectral photogrammetric technologies with primary data acquired by UAVs. The experience carried out in an impervious alpine territory foresees the close relationship of integration of photogrammetric techniques in the visible and the multispectral ranges, with the integration of terrestrial scanning solutions from slam-based mobile systems, to validate the results provided by the analysis of the spectral signatures of different kind of soils.

1. INTRODUCTION AND FRAMEWORK

Possible data integration strategies or fusion of image and range-based techniques are constantly investigated and developed to support the revitalisation of territories and valorising their significant landscape heritage. The so-called Inner areas (marginal areas rich in environmental and cultural resources but far from essential services) represent a valuable heritage where case studies requesting effective and low-cost solutions of geomatic methods for the territory investigation; the new knowledge achieved by exploiting technological innovations can be directed to enhance the social and economic development of these regions.
However, the complexity that intrinsically characterises the cultural heritage of territories and the heritage buildings themselves causes only an integration between heterogeneous data, geometric and radiometric, that can provide adequate and proper 3D metric documentation. (Sànchez-Aparicio et al. 2018).
In fact, if often the information connected with the geometry of a digital model is highly suitable for carrying out deformations or decay detection analyses, in many cases, regardless of the resolution and the level of detail of the model, its spatial configuration is not always adequate to efficiently describe feature like material consistency or to analyse specific features, that, instead, may be effectively recognised and mapped from radiometric data (Randazzo et al. 2020).
Because of these reasons, it is easy to understand the importance of complete documentation that aims to generate enriched 3D models characterised by multi-layered informative contents, allowing the generation of value-added metric products and, overall, representing a powerful tool for heritage investigations.
The application of this strategy, however, can achieve interesting results not only in the use of well-established sensing techniques – e.g. laser scanning or digital photogrammetry from traditional optical images – but also (and especially) in less consolidated methods and techniques, when it is necessary to extract spatial information from data that traditionally are not used for metric purposes (e.g., multispectral imagery) (Moropoulou et al. 2018; Pronti et al. 2019).
Regarding these kinds of data, the extraction and fusion process is characterised by many unsolved bottlenecks and still needs to be consolidated, while the interoperability between formats and many other aspects negatively affects the possibility of generating these enriched 3D models. As will be reported in the next paragraphs for the case-study area, georeferencing issues, optimisation of the generated models and flexibility of the adopted strategies are some examples of critical issues that come across the process that, also because of the low level of automatism, often represents a problem in the perspective of reaching sustainable documentation of the asset (Patrucco, 2023).
Based on these assumptions, the current paper aims to compare the results obtained from integrating multispectral data and 3D point clouds acquired using a SLAM-based Mobile Mapping System (MMS) to investigate the presence of ancient underground fortifications. The 3D survey has been carried out near an alpine pass (Passo della Gardetta, Valle Maira, Piedmont, Italy), where the fortifications (dating mainly from the period before World War II) are located.
In this case, UAV photogrammetry, Mobile Mapping System (MMS), and multispectral data analysis represent three valid techniques that, strictly integrated, can provide a data fusion-oriented strategy supporting both the historical analyses of the site and/or the non-invasive monitoring of heritage buildings.

1.1 Related works

UAV (Unmanned Aerial Vehicles) photogrammetry represents a powerful resource that certainly can contribute to the investigations of natural and anthropic characteristics of the landscapes, allowing investigations of the earth's surface from a close-range perspective.
This technology is increasingly used in many research frameworks thanks to the versatility and reliability of recently developed commercial aerial platforms, the development of new sensors (Themistocleous et al. 2015) and the enhancements of

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georeferencing methods (Tomaštík et al. 2019), enabling investigations in critical areas. In fact, the UAV's ability to fly closer to the object and to access narrow spaces (Gerke, 2009) makes this method particularly useful and a significant opportunity for studying Inner areas (Sammartano & Spanò 2016), providing useful 3D data for GIS monitoring applications, as georeferenced information at from orthoimages and DSM (Yastıklı et al., 2013). Still, from a methodological point of view, another significant opportunity is also provided by the possibility of co-registering photogrammetric data acquired in the visible spectrum and multispectral images, exploiting the fusion capability in the photogrammetric workflow now offered by commercial software platforms.
However, multispectral images – provided by UAV platforms equipped with sensors allowing the acquisition of multispectral bands - and, consequently, multispectral analysis, among the many emerging methodologies, aren't traditionally used for architectural investigations. In particular, regarding the multispectral data analysis, the study of the spectral signature is widely used in the environmental and forest investigations fields (Belcore et al. 2021), in precision agriculture (Dubbini et al. 2015; Kharuf et al. 2018) and is particularly cutting-edge in hydrology processes observation (McCabe et al. 2017). However, in the last years, it was possible to witness an increasing application development in the field of non-invasive diagnostic techniques of cultural and archaeological heritage to evaluate how the presence of underground buildings or buried architectural artefacts may influence the characteristics of the vegetation and the soil above the analysed remains (Verhoeven et al. 2009). Specifically, archaeological features usually cause stress in the crops or soil above, which, expressed through reflectance value and registered by multispectral images, can be analysed with spectral indexes. These indexes, expressed through visualisation maps, enhance the vegetation/soil features, and allow to visually identify marks of different colours referred to the buried remains so it can be easier to try to identify their positions (Fuldain González et al. 2019).
Regarding emerging methodologies, the so-called MMS (Mobile Mapping Systems) deserve mentioning, in particular, because of their efficiency and time consumption. Specifically, in the case of handheld MMS, these features, added to the portability and compactness, are particularly effective and have been tested in many different configurations, demonstrating the instrument flexibility in indoor volumes or narrow environments survey, such as industrial spaces, tunnels, caves or also cultural heritage domain (Nocerino et al. 2018).
Another significant opportunity of this technology is provided by the possibility of integrating the MMS cloud with other clouds acquired by different systems with different resolutions and accuracy. As will be reported in the next paragraph, the integration between a mobile laser scanner cloud and a UAV photogrammetric cloud is particularly interesting for many reasons. First of all, in the case of MMS cloud geo-referenced in a local system – as for this study – the UAV cloud can provide the points for correct geo-referencing. Secondly, a well-established strategy is represented by the possibility of checking if and where there have been drift errors for MMS scans or problems during the acquisition process using TLS – terrestrial laser scanner – clouds as "ground truth". However, as already mentioned, in this study the reference cloud exploited for these purposes has been the UAV cloud.

2. METHODOLOGY

2.1 Aims and case study

The main objective of this study was to evaluate the possibility of identifying underground fortifications using photogrammetric multispectral data. The application scenario was the Gardetta plateau area and the adjacent Prato Ciorliero valley, both located approximately at 2300 m asl, in Maira Valley (Cuneo - Piedmont). The area – particularly known for its defensive features since the XVIII century – is still nowadays characterised by various testimonies of its warlike past, both more recent and of the late 18th century. Specifically, along the current excursion network, consisting mostly of old and disused military roads, it is possible to see both cave *operas* built during the Second World War but never actually entered into operation, which has been the case study of this analysis, and, with a slightly more critical eye, the remains of 18th-century entrenchments.
The terrestrial and photogrammetric surveys concerned three military structures – called "*opera*" 179, 180, 181 – built between 1938 and 1942, currently in a state of neglect and degradation.

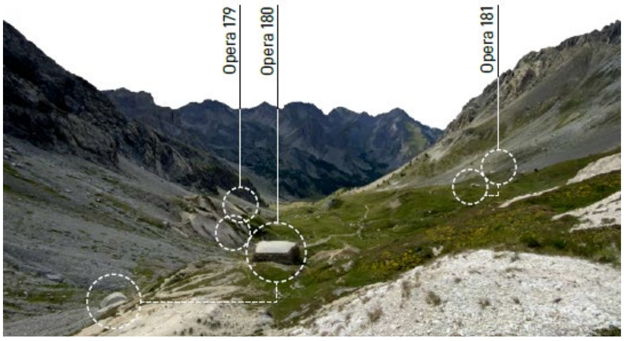

Figure 1. Twin emerged structures of 179, 180, 181 *operas*.

Figure 2. Outdoor and indoor views of the *opera* 180.

Each *opera*, made of concrete, according to military directives, is almost entirely underground, except for a very limited portion which is partially against the ground (typically against a hill or mountain's side) and used to access the structure or host the weapons. The concrete structure is in plain sight and except for collapsed area, the surface is particularly regular and without any remarkable features. Additionally, because of the damages and collapses, in many cases – opera 179 and 180 – weren't accessible in all their parts.

https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1419-2023

As shown in Figure 3, typically only *caponiera*, *malloppo* and – if present – the observatory is above the ground while the other rooms, the dormitory, all the corridors and stairs were built underground, using the topsoil mass as protection from attacks and explosions.

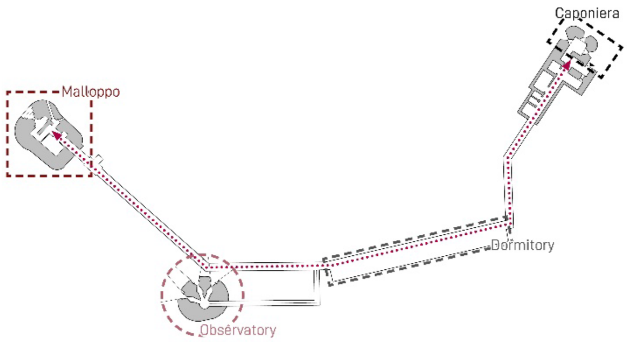

Figure 3. Scheme of a typical opera distribution.

Furthermore, the underground structure – which represents a high percentage of the *opera* – and in particular, the corridors and the dormitory are very extended. Typically, the dormitory, placed in the deepest area, is 25 m long, while globally, the *opera*, with the other spaces and the long corridors, can reach almost 100 m in length.

2.2 Acquisition critical issues

Based on these premises, the application scenario is specifically challenging for many reasons. Firstly, the significant altitude (about 2,000 m asl) and the morphology of the surveyed alpine pass, characterised by a significant difference in height between the extremes of the area and the narrowness of the valley, have prevented the programming of automatic UAV flights. All the photogrammetric acquisitions, in fact, have been carried out manually and, in addition, it was necessary to place several markers on the ground for the determination of Ground Control Points (GCPs) and Control Points (CP) since the RTK (Real-Time Kinematic) technique – considering the morphology of the place – did not guarantee the flight safety margins and the necessary precisions for the estimation of the camera positions during the flights.
Similarly, the terrestrial surveys of the Second World War fortifications - carried out using a SLAM-based MMS system – were challenging because of the geometric regularity of the underground concrete tunnels that caused the well-known problems of misalignments and trajectory drift errors (Farella et al. 2016).
Both methods and the general survey have been supported by the realisation of a topographic network consisting of 3 vertices (also useful to other areas surveyed and not referred to in this paper) and 13 markers, measured by GPS/GNSS system in both static (for the vertices) and RTK (for the markers) techniques. Specifically, the registered 3D accuracy of the markers was approximately 2-3 cm while – as shown in Table 1 – the vertices' accuracies were about 2 mm in x and y and about 5 mm in z.

Id	East [m]	North [m]	Height [m]	Acc. x - y [m]	Acc. z [m]
1000	340953.951	4919620.720	2511.796	0.002	0.005
2000	340942.619	4919458.063	2501.686	0.002	0.005
Rifugio	341891.069	4919171.854	2403.042	0.002	0.004

Table 1. Vertices' coordinates and their accuracies (shown in the last two columns on the right).

2.3 MMS data acquisition and processing

The terrestrial surveys of each bunker of the area have been realised using a handheld laser scanner (ZEB Revo RT by GeoSLAM) equipped with the Hokuyo UTM 30LX survey sensor and an inertial measurement unit IMU (Inertial Measurement Unit) with triaxial gyroscopes, accelerometers and three-axis magnetometers, instead of a GNSS receiver.
To achieve the best possible coverage of each bunker, both internally and externally, with the exclusion of non-reachable underground areas, it has been programmed to carry out two internal scans - sometimes, due to the presence of errors or internal drifts in the scan itself, even more than two – and an external scan, of longer duration and extension.
The first ones had to cover - whenever possible – both bunkers' blocks (*caponiera* and *malloppo*) inner rooms and their long underground tunnels. The external scans, instead, had to include both blocks and a portion of the neighbouring area (again, due to some errors, some scans had to be repeated). Because of the geometrical features and the underground position of the tunnels, many scans were characterised by misalignments and trajectory drift errors that caused a longer manual involvement on the part of the operator during the cleaning part of the process. In particular, in case of scans too overlaid and deformed, it has been useful to segment, clean and compare each cloud with existing archive designed plans obtained by *Primo Reparto Infrastrutture* of Turin.

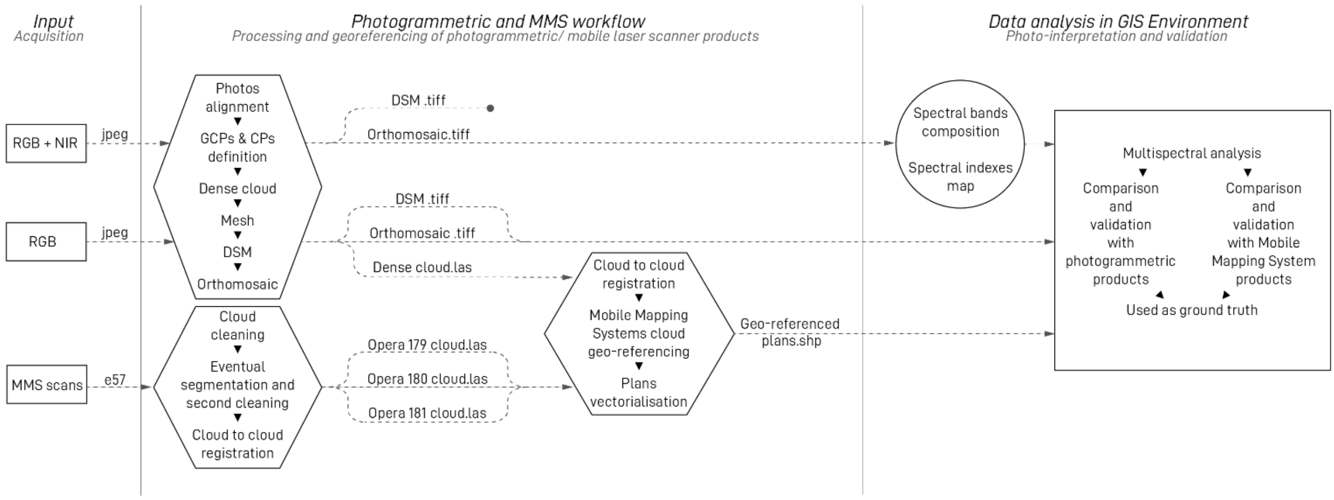

Figure 4. Scheme summarising the data processing and information extraction workflow.

Once final scans had been obtained – two or three per bunker - it has proceeded with their registration in the same local reference system. This operation has been particularly onerous for the operator because of the - already quoted - regularity of the interior spaces and also because of the roughness of the external walls of the "opera" that constitute, at this stage, an obstacle, as they cause difficulties in the homologous points' matching. Furthermore, the external MMS data acquisition – and consequently the registration of the scan - has also been affected by the lack of appropriate outdoor features useful for the correct outdoor functioning of the SLAM algorithm. In fact, while on the one hand, as customary in military defence structures, the outer surface of the bunkers is extremely limited and partially against the ground, on the other, at this altitude, there aren't many other SLAM-suitable features, apart from usually non-functional grass and a few stones.

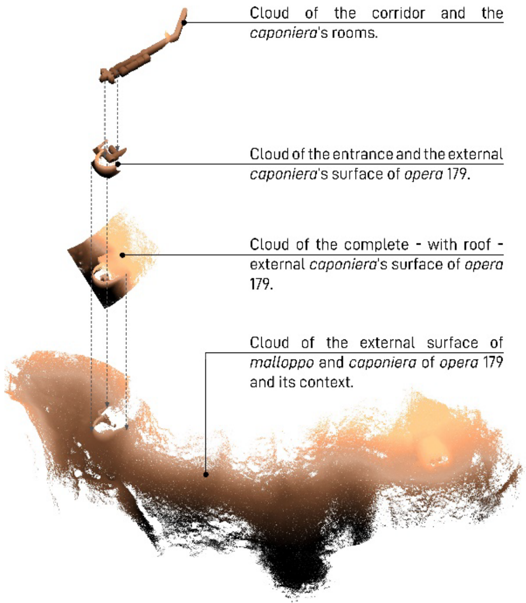

Figure 5. Scheme of the alignment of opera 179's scans.

However, each bunker's internal scans have been registered using the external scan as a reference and 5 – 7 points of alignment. This technique worked very well for 2 of 3 bunkers in which the scans didn't reach all the rooms, so it didn't make a closed path, but only a round trip could have been adopted. Generally, the average RSME for these two bunkers registered final cloud is settled about 5 cm. On the other hand, in the third bunker (n.181) – totally surveyed – two of the scans acquired in the corridor area, probably because of the trajectory drifts errors, did not align. These, in fact, although apparently congruent in an initial visual inspection, at the moment of alignment, showed a drift of the one in relation to the other of approximately 50 cm that increased the average distance of the points chosen to align the two clouds.
This problem has been fixed by splitting the cloud into two parts - the corridor and the dormitory – that, aligned in two different steps with the external scans, led to the best result in terms of registration. However, the final cloud obtained for this bunker shows a misalignment in the corridor of approx. 20 cm. This is a global mismatch which, given the premises and the challenging application scenario – characterised by almost hundreds of meters long structures, nevertheless represents a very good result, entirely consistent with the aims of the study. At the end of the processing, it has been obtained a complete cloud for each bunker, geo-referenced in a local reference system. For this reason, another step of georeferencing is useful and has been realised by exploiting the photogrammetric flight dense cloud, used as ground truth, as will be reported in the next paragraph.

2.4 UAV visible and multispectral data: acquisition and processing

During the survey, two types of UAV data acquisition were realised: visible and multispectral. The first one was carried out using a UAV system (DJI Mavic Pro) equipped with a single CMOS sensor for the acquisition of high-resolution images in the visible spectrum, while the second one was realised using a UAV system (DJI Phantom 4 PRO RTK Multispectral) equipped with five CMOS sensors allowing the acquisition of multispectral bands in a specific range of the electromagnetic spectrum: blue (450 nm ± 16 nm), green (560 nm ± 16 nm), red (650 nm ± 16 nm), Red-Edge (730 nm ± 16 nm), and Near Infrared (840 nm ± 26 nm). Additionally, a sixth camera recording visible light is present.

UAV Model	DJI Mavic Pro
Sensor	1/2.3" CMOS
Effective pixels	12.35 [MP]
Lens	5 [mm] (35 mm equivalent: 26 mm) Field of view 78.8° Aperture: f/2.2
Image size	4000 x 3000 [pixels]

Table 2. Main specifications of DJI Mavic Pro camera.

UAV Model	DJI Phantom 4 PRO RTK Multispectral
Sensor	Six CMOS 1/2.9"
Effective pixels	2.08 [MP]
Lens	5.74 [mm] (35 mm equivalent: 40 mm) Field of view: 62.7° Aperture: f/2.2
Image size	1600×1300 [pixels]

Table 3. Main specifications of DJI Phantom 4 PRO Multispectral camera.

For both flights, the acquisitions have been planned in order to pay particular attention to the overlapping between images, following the well-known photogrammetric acquisition principles. In particular, the acquisitions have been performed with both nadiral and oblique configurations with the aim of covering the entire surface of the emerging portions of each bunker. They covered approximately the same area with different flight altitudes: 40 m in the case of visible acquisition and 100 m in the multispectral one. However, because of the different weather conditions during the flights and the difficulty in the identification of the remains of the bunkers, the multispectral acquisition missed a portion of the central bunker and his swag. For the same reasons, in order to optimise flying times, this flight has been realised in a much faster and more expeditive manner without setting up a radiometric calibration panel.
The impossibility of estimating the coordinates of the camera centres during the acquisition represented the most relevant bottleneck of the processing of both flights. For this reason, it was necessary the collimation of the measured GCPs and CPs. The points have been marked in all visible images (993 images) and, in particular, in all the bands of the multispectral images (286 images x 5 bands) to optimise misalignments and geometric co-registration errors between the different spectral bands.
In general, the average RMSE - reported in Table 5 - for both visible and multispectral flights is settled around 5 cm, which is considered acceptable for the proposed application, especially in relation to the two different GSDs reported in Table 4.

	N. images	Tie points	Dense cloud	Estimated GSD [cm/pixel]
Visible dataset	933	1,742,667	260,198,625	2,35
Multisp. dataset	1430	195,473	15,824,880	9,69

Table 4. Main details of the photogrammetric process (true colour and multispectral datasets).

	RMSE [cm]				
	n	X [cm]	Y [cm]	Z [cm]	Total [cm]
Visible acquisition GCPs	9	2.455	2.621	4.193	5.521
Visible acquisition CPs	3	3.930	2.075	4.551	6.361
Multispectral acquisition GCPs	5	2.675	1.006	2.889	4.063

Table 5. Mean errors on GCPs and CPs for visible and multispectral datasets.

The visible dataset allowed to generate a dense point cloud and to achieve high detailed 3D model and the generation of value-added metric products of the portion of the fortifications and their neighbouring area. Instead, the point cloud obtained from multispectral images generated value-added metric products of the same area with a lower quality due to the lower resolution of the multispectral cameras, useful for the following step of the analysis.
Both clouds and products, thanks to the GCPs and CPs collimation and the consolidated processing through the well-known software Metashape, are so geo-referenced in the same reference system EPSG: 32632 – WGS 84 / UTM zone 32N.

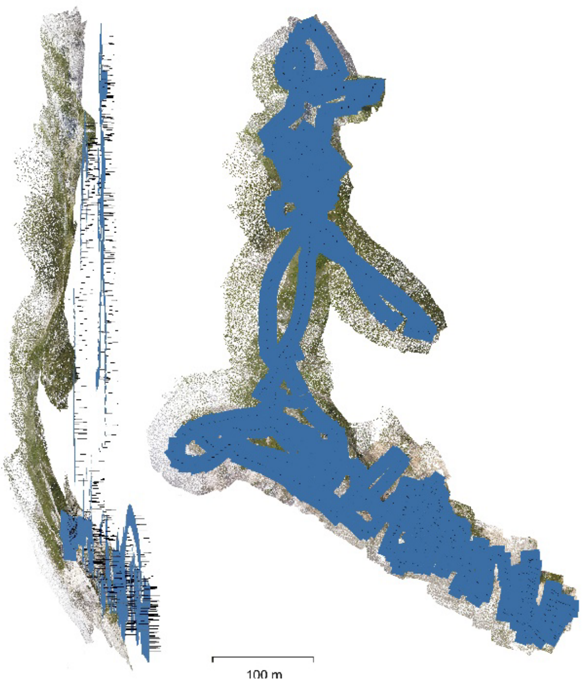

Figure 6. Side and top view of spare photogrammetric dense cloud and camera centres.

2.5 Georeferencing and validation of MMS data

The preliminary visible-photogrammetric flight has been used to geo-reference terrestrial 3D surveys carried out using the portable MMS, which was able to detect the remains of the fortifications regarding both the emerging portions and the underground structures, enabling the referencing of the buried areas. However, the laser scanner cloud, as expected, compared to the photogrammetric one, possessed a lower level of detail, which, also considering the geometry of the fortifications and their context, meant that the alignments were characterised by not so contained discrepancies. The deviations resulting from the best alignment obtained between the slam-based and photogrammetric clouds – realised on 3DReshaper - are approximately 20 cm (bunker 180) and 50-55 cm (bunker 181).
For this reason, it has been decided to make an optimisation in the vectorisation phase, exploiting the possibility of georeferencing the bunkers' raster plans – exported by PointCab - on the true colour photogrammetric orthophoto in GIS environments through a polynomial transformation. Exporting the correct geo-referenced raster plans, the vectorisation of plans and sections has been carried out. This non-canonical procedure, however, has been only a secondary method used to improve the alignment performed between the different clouds, which, as already mentioned, provides not entirely satisfying results.
At the end of the processing, using the GIS environment's capabilities, it was possible to compare each method's results and then obtain a complete documentation of the fortification's area and its inner parts, characterised by multi-layered informative contents. In the same project, in fact, it has been possible to achieve the comparison between the geometrical features of the inner and external part of the fortification and the complexity of Prato Ciorliero valley, provided by both the photogrammetric visible orthophoto's and the slam-based scanning's cloud and their radiometric information, provided by the photogrammetric multispectral orthophoto. Specifically, the terrestrial surveys have been useful to subsequently evaluate and validate the multispectral anomalies detected during the analysis.

3. ANALYSES

3.1 Multispectral data Analyses

As already reported in paragraph 1.2, the vegetation and soil indexes have been used in support of the identification of the possible presence of underground built remains. For the analysis of the multispectral orthophoto, observing a similar methodology, the following indices have been considered, focusing on the spectral signatures of vegetation and soil: NDVI – *Normalized difference vegetation index*, NDRE – *Normalized Difference Red Edge*, GNDVI – *Green* NDVI and BI – *Brightness Index*, which considers the humidity and the presence of nitrates to identify variations in the soil impoverished by possible underground structures. Additionally, other two band combinations, NAI (*Normalized Archaeological Index*) and RN (Red-NIR), successfully applied in previous archaeological research experiences using satellite images (Agapiou et al. 2014, Zanni & De Rosa 2019), have been tested in the present case, allowing the detection of non-visible features coherent with the presence of the underground structures.
The calculation of spectral indices and the following interpretative analysis was carried out, once again, in a GIS environment, exploiting the possibility of using advanced tools for band management and their representation.
The choice of the software hasn't been arbitrary and, indeed, was linked to its potential in the field of multispectral analysis, allowing it to be carried out in a simple but effective way, but

also to the possibility of bringing together previously collected heterogeneous data in a single environment, with the ability to efficiently relate them.

Two different applications of the analysis have been performed. The first one concerned the possible identification of underground artefacts and the indicative recognition of their planimetry. The idea has been to test a methodology to verify the presence and general dimensions of an underground structure, as in this case, exploiting the technologies typical of Remote Sensing that allow investigations and analyses to be carried out remotely without the need for direct contact with the studied artefact. The second attempt at the application of multispectral analysis, on the other hand, was aimed at the search for collapses, detachments and fractures in the cave *operas* in order, once again, to verify their presence and, in general, to check the condition of the artefact without necessarily accessing it.

3.1.1 Opera 179 & Opera 181

Concerning the first analysis application for *opera* 179, the NDV index revealed a medium/low growth of vegetation (as well as extensive areas of bare rock) in the area above the initial section of the corridor of the buried manufact. This result has been compared to the NDRE index that showed stressed or unhealthy vegetation: while the surrounding area is of an intense green, the portion on the corridor appears lighter and with values close to 0 (<0 Inanimate or dead object, 0 - 0.3 Unhealthy or stressed plant material, 0.3 - 0.6 Moderately healthy plants, 0.6 - 1.0 Very healthy vegetation).

(a)

(b)

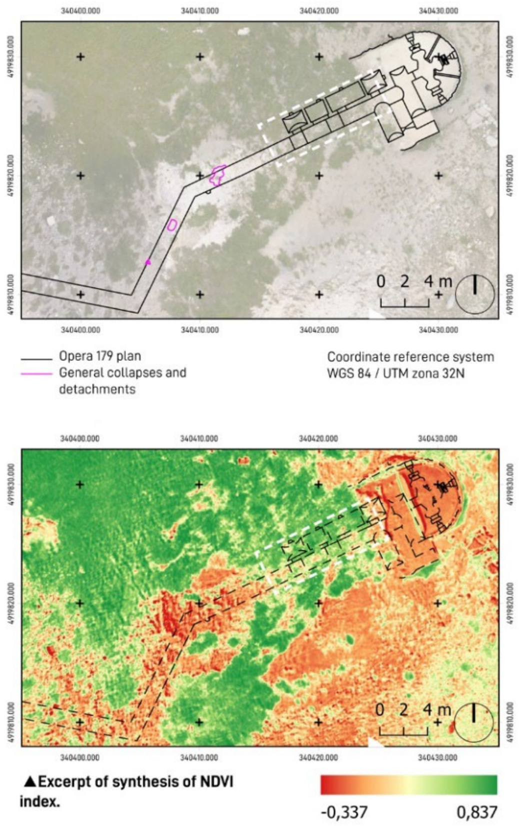

Figure 7. Comparison between visible orthophoto (a) and NDVI map (b) with the identification – in white - of corridor of opera 179.

Similar pieces of information have also been provided by the GNDV index. This data, then, have been compared to the information provided by the visible-range orthophoto and the slam-based’ clouds, used as ground truth. The result of this comparison displayed how the perimeter of the low vegetation area followed, in a certain way, the development of the underground corridor and many of the nearby rooms, provided by the geo-referenced plans of the *opera*, itself obtained by the MMS cloud.

The second analysis application punctually worked on the visualisation range of the spectral indices and the comparison between that data, the visible orthophoto and the geo-referenced plans of each *opera*. This process allowed the analysis to be limited to 3 areas (shown in the coloured orthophoto): a small clod of green that, overlaid to the georeferenced plan of *opera* 179*,* is located approximately a few metres from the curve of its corridor; two areas near the corridor and the dormitory of *opera* 181.

(a)

(b)

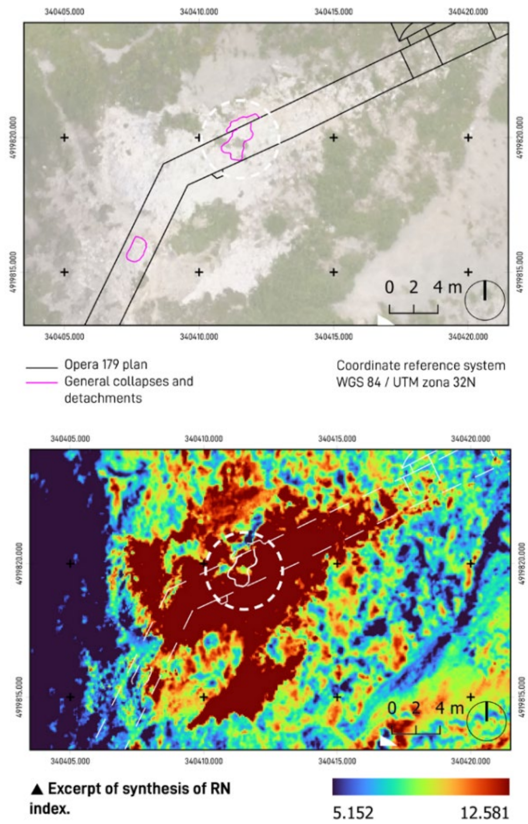

Figure 8. Comparison between visible orthophoto (a) and RN Index map (b) with the identification – in white - of corridor’s collapse in opera 179.

Firstly, all three areas have been spotted on the NDV index visualisation and then, checking on the other indexes’ maps, have been clearly identified. NDV index highlighted, as in the previous case, low growth of vegetation – represented by a lighter colour compared to the context – in these zones that, instead, on the visible-orthophoto, appeared all with the same amount/size of vegetation.

However, the RN (Red-NIR) index provided the best visualisation results. RN, in fact, considers the NIR band, in which vegetation re-emits more intensively and has a higher spectral resolution, given by the sum of the two bands, that makes it possible to highlight areas – as the ones already reported - with a higher reflectance. Compared to the reflectance of the surrounding vegetation and also to the one of the bare rocks, the areas under investigation present values that are in the second upper half of the reference scale of the index (high values = high reflectance and suffering vegetation, low values = low reflectance and healthy vegetation), referencing to a stressed and not healthy vegetation compared to the one on the surrounding surface.

To better understand the reasons of these areas, an important step has been the comparison between multispectral and terrestrial data, as for the first analysis application, in which the georeferenced laser scanner point cloud – and the consequent graphic restitution – has been particularly helpful. A comparison between the georeferenced plans and the spectral indexes maps allowed to understand that the enlightened areas were located in the same place where – a few meters under the surface – the bunkers were characterised by collapses and detachments. The fortifications' underground concrete structures, in fact, during years of neglect, suffered many collapses that affected mostly the rooms and corridor concrete walls, vaults and, consequently, the rocks behind/above.

(a)

(b)

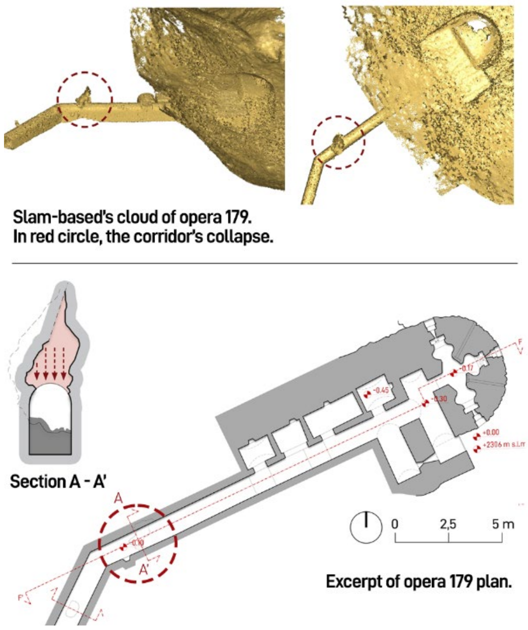

Figure 9. Slam-based's cloud (a), plan and section (b) of opera 179.

In particular, the area detected near opera 179 matched a big collapse of the corridor's vault of the bunker – highlighted by the slam-based cloud – a few meters underground that reached a certain depth in the rock, probably affecting the growth of the vegetation above it.
Regarding opera 181, the two detected areas matched two big collapses in the second half of the fortification – in the north, near the swag. The first was on the dormitory's north side, while the second was in the anti-gas room.

3.1.2 Opera 180

On the contrary, *opera* 180 provides an example of how the spectral elements of photointerpretation can sometimes lead to erroneous conclusions if not properly validated, e.g., example, by examining geometric elements provided by other traditional surveying techniques (e.g., the shadow of the analysed element supplied by the photogrammetric orthophoto).
In this case, in fact, both NDVI and GNDVI (in reality, also other indexes produced entirely similar and consistent results, so they have been omitted) highlighted two clear marks on the ground around the caponier of opera 180. After a comparison with the visible orthophoto, nothing particularly relevant appeared, nor did such clear differences between the terrain and vegetation, useful to explain these traces characterised by high radiometric contrast. For this reason, a second comparison has been made with the visible orthophoto obtained from the multispectral flight and derived from the synthesis of the three RED, GREEN and

(a)

(b)

(c)

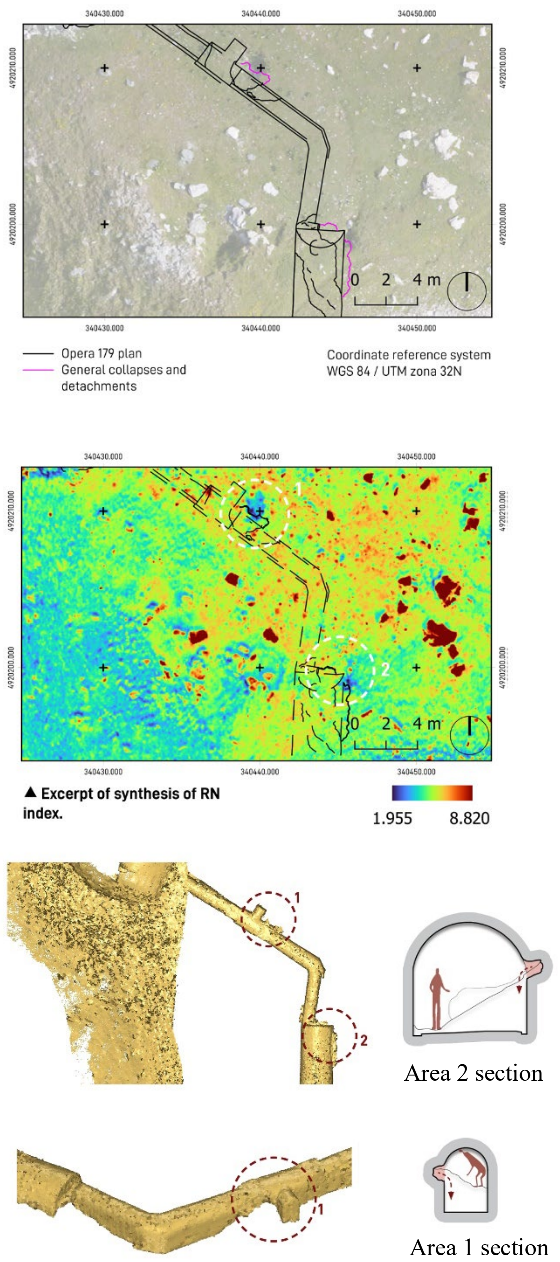

Figure 10. Comparison between visible orthophoto (a), RN Index map (b) and slam-based's cloud (c) with the identification – in white and red circles - of corridor's collapses in opera 181. On the right, sections of the collapsed areas.

BLUE bands obtained from the multispectral camera flight. This one allowed to understand that those detected marks derived from the shadow of the caponier projected on the ground, which, incidentally, generated the same effect in the vicinity of the entrance, another area in the shadow of the structure. These shadows, in particular, didn't appear in the first visible orthophoto because the flight was made at a different moment of the day – late afternoon – and with different weather conditions, in comparison to the multispectral flight, performed in a cloudy morning, which influenced the shadows' projection on the ground.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The analysis of the multispectral data applied to the considered military structure was developed with the aim to identify both the

presence (and approximate location) of the analysed artefacts and the internal collapses of the underground structures and was considered an interesting method in reaching complete documentation of an artefact. The proposed application, in fact, can be considered an additional technique useful in obtaining enriched 3D models characterised by multi-layered informative contents, able to display all the complexity of the built heritage.
The promising results suggest that (under certain conditions) it is possible to identify the underground structures and preliminary check the buried buildings' conditions (often characterised by precarious safety conditions) without necessarily accessing them. This particular element is a valuable advantage, specifically considered fragile artefacts, objects and areas that need to be surveyed safely, accurately and adequately.
Additionally, in the presented case, the visible photogrammetric orthophoto and, above all, the georeferenced slam-based point clouds – used as ground truth – have been crucial to allow the validation of the proposed methodology and, contemporary, to define one of its limits. In fact, it should be underlined that extensive portions of the tunnels of the analysed structures are developed in significant depth (even more than 10 m deep), not providing – therefore – evidence on the surface near the ground level. In other words, the proposed methodology is applicable only in the areas where the underground structures are relatively close to the ground surface and, therefore, the proximity of buried artefacts influences the vegetation and soil characteristics or, similarly, in damaged areas in which the collapse has been so intense and deep that influenced the rocks and soil above.
Furthermore, another aim of this study is to point out the contribution of multispectral analysis, in the sense of an integrated technique to achieve an adequate and proper 3D metric documentation of the cultural heritage of territories and buildings and capable of adding a new layer of data to the ones acquired through traditional techniques.

5. ACKNOWLEDGEMENTS

The 3D survey experience in the Passo della Gardetta area (Valle Maira, Piedmont, Italy) has been performed as didactic training by the student team DIRECT of the Politecnico di Torino.

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