# Fostering Etruscan heritage with effective integration of UAV, TLS and SLAM-based methods

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# Fostering Etruscan heritage with effective integration of UAV, TLS and SLAM-based methods

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***Abstract* – The paper has the main role of highlighting the advantages resulting from the combination of different 3D survey methods and how the approaches that involve data and methods fusion can be advantageous in cases where the environment in which one operates is particularly impervious and not very inclined to be faced with traditional solutions. UAV Photogrammetry, TLS and the innovative 3D scanning based on SLAM technology are combined for the investigation and the documentation of a suggestive landscape and archaeological park. The hand held SLAM based scanner, capable of generating the point cloud travelling among complex indoor and outdoor environments, detecting even small defined spaces, has proved its fundamental importance for the knowledge and reconstruction of the landscape of a particular category of ancient heritage: the necropolis of the caves of the Baratti e Populonia park, which lies in a suggestive scenario of rich and dense forest.**

Keywords: UAV Photogrammetry, SLAM (Simultaneous Localization and mapping), 3D models, multiscale models, Methods fusion.

## I. INTRODUCTION

For many years, the integration of consolidated and innovative image and range-based methods has proven to be a particularly advantageous strategy in the general framework of Cultural Heritage documentation for preservation, and even in the archaeological research and ancient heritage scenario. [1,2]
The most interesting aspects are not only limited to the flexibility, the richness of geometric and thematic information, the metric accuracy and density of spatial information deriving from the application of separate 3D survey methods, but in their collaboration.
In the present paper, the advantages obtained from the integration of cutting-edge methods for 3D metric survey useful for the representation of data obtained in a mapping environment will be addressed and examined. The data acquisitions, obtained with different methodologies, have allowed a different resolution and scale of detail of the investigation within the vast Tuscan Archaeological Park, which is characterized by marked landscape dimensions alongside archaeological objects, the Etruscan necropolis, which require typical approaches of the architectural scale for ancient remains.
In particular, by combining SLAM-based and terrestrial laser scanner (TLS) methods, it was possible to integrate effectively UAV based DSMs, in order to detect elements otherwise not visible from the aerial point of view and obtain a 3D model satisfying very different scale needs.
The application of rapid mapping systems has allowed pursuing various possibilities of integration and data fusion, using a targeted choice of systems from a large variety of different sensor solutions introduced into the market. The generation of an integrated, complete and geo-referenced 3D model of the archaeological park foreshadows the possibility to translate the 3D data processed into digital datasets for mapping the environment, making it possible to carefully update the paths map of the park, which until then had presented lacks and inconsistencies.

## II. FRAMEWORK OF METHODS AND DATA FUSION IN HERITAGE DOCUMENTATION

The aerial point of view and therefore remote sensing has always played a fundamental role in archaeological research, and the significant and by now consolidated diffusion of UAV photogrammetry in archaeological documentation has had the role of bridging the gap between terrestrial and aerial techniques. [3, 4, 5, 6, 7]
The nowadays increasingly customary and shared acquisition procedures of UAV oblique images that has

re-revolutionized the methods of heritage modelling from close-ranges, also by means of mini UAVs that are particularly easy to manage and can fly safely close to objects of interest, is one of the most popular fields of investigation. [8, 9]
An emerging and very promising field of exploration is that of the evaluation of the accuracy of photogrammetric products derived from the use of UAV platform equipped by GNSS receivers flanking RTK technique to realize direct photogrammetry applications. [10, 11]
The development of co-registration algorithms of oriented image blocks using the same reference system [12], or applied to image and range based data [13] has made clear how useful they can be in different applications. That has been proved to be feasible even using sensors other than the visible, (multispectral, hyperspectral and thermal), as well as in the development of multi-temporal applications [14].
Approaches that aim at methods fusion and combine datasets acquired from different sensors by exploiting co-registration algorithms or even ICP (iterative closest points) algorithms can be effectively employed by combining aerial and ground data, such as emerging laser scanning methods based on SLAM, to achieve optimization and even geo-referencing purposes. [15]
As emerging from recent literature, among MMS (Mobile Mapping Systems), portable hand-held scanners, based on the SLAM algorithm, are able to produce dense and well-detailed clouds by exploiting the movement of the operator in the space to be detected, both in external and internal environments. [16, 17] SLAM technology allows to determine the position of the moving instrument carried by the operator or the moving device while detecting a certain environment, through the estimation of the trajectory and the continuous alignment of the acquired point clouds, using the ICP strategy. The advantages ascertained by numerous experiments of this method are essentially the portability and flexibility of the system, the possible use in complex environments, the speed of acquisition which is not comparable to the traditional TLS method and the fair level of detail, with suitable accuracy for the 1:100 and 1:200 scale of representation. Although these favourable conditions are present in many different applications, the combination of some of them is particularly suitable in case of landscape assets. [18] In these cases, in fact, it is important to document both the environmental context of reference, involving natural elements, and the morphological features of heritage assets; the SLAM-based clouds can be a valid alternative to traditional solutions, that could be particularly expensive in terms of time-cost balance [19].

## III. CASE STUDY: BARATTIAND POPULONIA ARCHAEOLOGICAL PARK

The Archaeological Park of Baratti and Populonia (Fig1) extends to the slopes of the promontory of Piombino and the Gulf of Baratti. It is a real open-air museum, where the soil of the necropolis is rich in ferrous slag as evidence of the imposing presence of an Etruscan industrial city. [20]
The necropolis of the Hellenistic period is inserted in a very extensive wooded area and has groups of underground tombs carved into the rock. This natural configuration, wisely chosen by ancient civilization, poses numerous challenges for documentation methods, which must adapt their capabilities to the complex framework of interaction between the natural environment and anthropogenic presences.
The surveyed area extends for about two square kilometres, presenting a significant difference in height; along the slope numerous groups of underground tombs are widespread, with the exception of the large Cava delle Grotte located in a large abandoned cultivation plane, which was used as a reference environment for the georefencing process of the acquired data.

Fig.1. *Aerial view of the* Cava delle Grotte *and the Archaeological Park of Baratti and Populonia near the promontory of Piombino*

The Cava delle Grotte (Fig1) can be considered the core of the great Necropolis of the Caves, the largest of the Hellenistic necropolis in Populonia between the 4th and the beginning of the 3rd century BC. The main interest of the area is the large rock wall carved by quarrymen in the seventh and sixth centuries BC, the only portion of the necropolis not yet completely overlooked by dense vegetation. Given the ease of carving the rock, the Etruscan world, now at the drip, has built many burial chambers inside it. [21]

## III. FUSION-BASED 3D MAPPING TECHNOLIGIES FOR THE PARK UPDATING

In order to operate for the 3D mapping and updating of the park context in the Etruscan Necropolis of the Caves, consolidate and cutting-edge technologies have been selected in the integrated approach (Tab.1) [22].
The use of topography and terrestrial LiDAR scanner has been deployed with the UAV photogrammetry and the innovative 3D MMS based on SLAM technology.

First of all, a complex control network was set with two hierarchy levels: the 1st order control network vertices, located in the sparsest areas of the park, has been set to homogeneously surround the park area and to allow the base GNSS receivers for Real Time Kinematic-RTK measurements finalized to GCPs positioning with high precision. A 2nd order control network has been set and measured in the more enclosed areas near the principal sites, with the help of topographic measures with total station. From those vertices a set of detail points were measured too, supporting both the scans co-registration and the photogrammetric bundle block adjustment.
The topographic network design (Fig.2) allowed to manage the whole survey involving a very wide area in the same reference system and accurately combining multiple sensor data.

*Tab 1. Integrated approaches applied in the archaeological park survey*

| | |
|---|---|
| 1st order control network | - *GNSS measured vertices bases* |
| 2nd order control network | - *Topographic measures*<br>- *RTK measures of GCPs* |
| Detail survey | - *Terrestrial laser scanner*<br>- *Close-range photogrammetry*<br>- *SLAM mobile mapping scanner* |

The particular topography of the site required an attentive planning of the integration of technological approaches and the detail scale of the 3D survey in order to study and document the Baratti & Populonia Archaeological park area. The UAV photogrammetric DSMs will be integrated together with the close-range photogrammetric ones and with the Lidar point models by TLS and SLAM-base scanner.
The whole area has been surveyed from the aerial point of view by drones using two different platforms with specific features according to the required extension and scale of the flight and details on the objects too.
The UAV photogrammetric acquisitions have been performed with a fix wing drone, the Ebee by Sensefly, equipped with the camera Canon Powershot S110 (12.1 MP sensor) and with a multicopter, a DJI Phantom 4 Pro platform (20MP sensor and 4K video quality).
The fix-wing ultra-light platform surveyed an area of almost 2km$^2$ wide corresponding to the whole park: the flight plan involved n°6 flight blocks and an amount of 760 photos captured in nadir-only configuration, with a mean flight height of 180m a.s.l., with an expected GSD=5cm.
The use of measured control points on the ground, captured by the images blocks, supported the bundle block adjustment phase and the georeferencing of the DSMs, and it was a crucial phase due to the presence of a deep and continuous canopy. Anyway a set of almost 20 points have been measured.

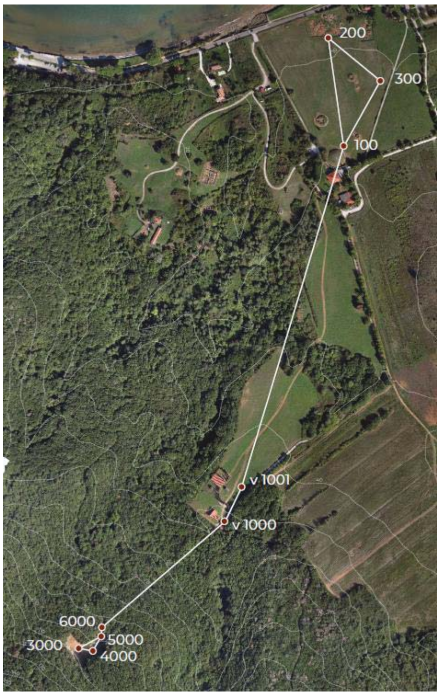



*Fig.2. Topographic network overlaying the orthophoto generated by the fixed wing UAV flight*

The metric accuracy of the 3D model verified on them delivered the results reported in Tab.2. The total error result demonstrated, in Z error, the lack of the oblique perspective on objects in the block adjustment: the influence of the oblique point of view, in a so high flight elevation, in fact, would have benefited from GCPs positioning on vertical surfaces, and in the same way, the final error result in Z dimension.

*Tab.2 The accuracy control on GCPs and CPS for the photogrammetric block*

| | X error | Y error | Z error (*m*) | Total error |
|---|---|---|---|---|
| GCPs | 0.017 | 0.014 | 0.213 | 0.030 |
| CPs | 0.0073 | 0.016 | 0.205 | 0.027 |

In parallel, with the aim of integrating the aerial UAV-based data and complete the ground-level documentation along the park paths and in the main interest sites, two scanning approaches have been tested in this complex archaeological extensive context.
The terrestrial Lidar scanning system, employed particularly for the Cave Necropolis, allowed the fast and accurate recording of a great amount of 3D points with geometric and radiometric information. The TLS data have been co-registered based on contrast markers measured with topographic approach, in the unique reference system and then filtered, cleaned and optimized in order to be integrated with other sensor data and then used for the meshing of 3D model. The n° 18 scans, divided into two blocks have been registered based on

ICP-like algorithm with an average value of about 2mm deviation (with almost 70° points under 4mm deviation). The use of marker alignment for the geo-referencing of the scans block retrieved a result of 15.4mm and 7mm st.dev. The integration of the ZEB-revo scanner have been tested too. The portable mobile mapping system in fact has been investigated in the park along the pathway under the dense canopy, with a complex and crossing series of scans up to the Necropolis of the Caves, especially the last segment of the path of the Quarries (from the Centre for Experimental Archaeology to the Necropolis of the Caves), crossing a long path in the rich wooded landscape of the park.

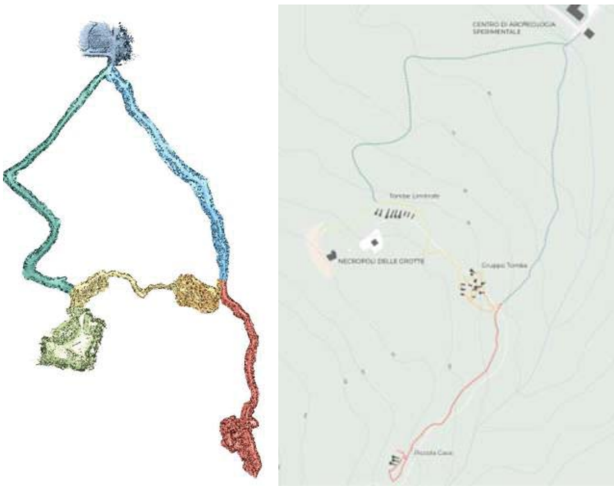



*Fig.3. The cloud derived from SLAM based Zeb Revo hand held scanner after the merge process. The digitalization of georeferenced cloud provides the chance to integrate the results in topographical dataset of forest paths within regional digital mapping*

The application of this tool in the current configuration of the park allowed the updating of the Park's cartography and the spatial geo-referencing of the numerous underground tombs found in the path towards the quarry.
The advantages from the use of the SLAM-base scanner, thanks to the operator action of walking along the footpaths, are several. First of all, the seven scans acquired along the wood and the clearing of the Cave and the Tomb 14, have been co-registered between them in a local reference system thank to the overlapping areas between the scans path in the join areas (see connections in Fig. 3). In a second phase the entire SLAM-based point cloud has been georeferenced with the UAV-based DSM with many crucial operative issues, due to the fact that the overlapping areas for the ICP-like fitting, or manual translation based on point-to-point, are very few. [22]

After a set of attempts in order to find the accurate positioning and identifying the optimal strategy, both manual and automatic, for the georeferencing purposes, the point cloud derived from the MMS is able to complete the documentation of the park and paths between the interest point of the archaeological area. The final result with residual deviation errors is reported in Fig.4 (*3D Reshaper* by Hexagon software interface have been used) and shows, in a zoomed view, the alignment between the two 3D surfaces.

*Fig.4. The process of co-registration between the georeferenced UAV DSM and the SLAM-based scans, supported by the common areas where the visibility is allowed both from the aerial and the terrestrial view*

The final check of the contours profiles from sections have been implemented to validate the accuracy of alignment and monitor the presence of drift errors due to the very long trajectories of topographically complex terrain. The integrated 3D data have been optimized to be managed with GIS tools in order to update the existing cartography of the park and implement new objects in the 2D/3D representation at high scale detail (1:200-1:500 concerning the mapping purposes of the park).
Moreover, the fusion-based 3D model strategy for the necropolis Cave benefits from the contribution of 4 data acquisition methods (Fig.5): static LiDAR for the main cave wall; UAV photogrammetry for the topographic context survey and the higher surface of the structure; SLAM-based portable scanner for the interior of the tombs and cavities; close-range photogrammetry for the texturing phase, adding high-quality radiometric information.
Particularly, the photogrammetric images block by drone is derived from a HD video performed with the DJI camera equipping the UAV platform. From the video, a set of extracted frames have been processed for photogrammetric purposes, using the detail points measured both on terrain and on the structure facades.
The terrestrial close-range photogrammetric block has been acquired with a Canon EOS 5DS R camera.
Starting from the integration of the photogrammetric data it was possible not only to acquire the information on the rock carving in the top part of the quarry, not detectable by the laser or MMS solutions, but also to use the set of nadir and oblique oriented images blocks for the following texturing of the fusion-based 3D triangulated model. [22]

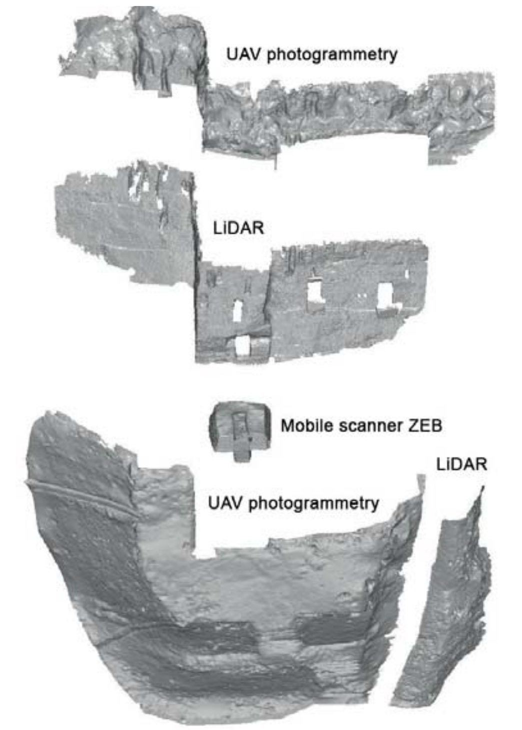
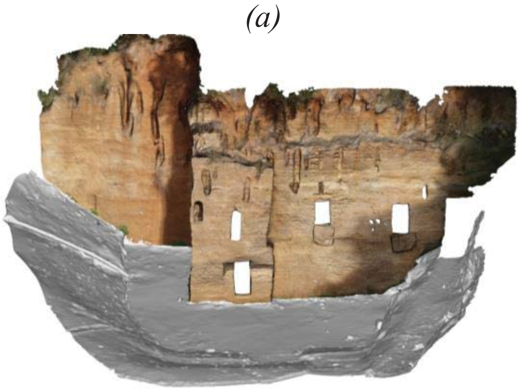



*Fig.5. Multi-sensor integrated point cloud model optimized in 3D mesh of the Cave Necropolis.*

*(a)*



(b)

*Fig.6. The fusion-based final mesh model of the Cave Necropolis (a). Texturized mesh model with almost 100 frames from UAV flight video, composed by two and a half million triangles (b).*

Operatively the optimization of the different point clouds (Fig.5-6) has regarded, and summarized as following: point cloud segment and cleaning, noise reduction, vegetation elements removal, creation of the polygon mesh, check of the normal vectors orientation, mesh smoothing and optimization including manual and local operation, and finally the texturing of the complete model of the Cava delle Grotte using the photogrammetric oriented block, located in the same reference system, as well. [22] The final high-definition 3D model of Cava delle Grotte is represented in Fig.6a, without and Fig.6b with the texture data component on the surfaces.

## IV. CONCLUSION AND FUTURE PERSPECTIVES

The technological research towards the use of advanced techniques that are more and more efficient, but also easily available, allows the experimentation and development of operational tools for documenting heritage context also in wide areas as the archaeological parks. In fact, in recent years, the rapid mapping survey extremely change its perspective with the possibility of this kind of portable solutions as a revolution of the traditional survey or more consolidated 3D data capturing.

Moreover, the optimization of the spatial value of this data, together with the possibility to give them their geographical position, plays an important role in the direction of the construction and updating of spatial databases and regional or municipality cartography. In fact, in the Baratti and Populonia Archological park (Fig. 7) the promising fallouts resulting from the integration of SLAM-based data and UAV mapping is the elaboration of a complex and accurate cartography in a GIS perspective, with challenging issue deriving to the treatment of this kind of data from a terrestrial point of view.

*Fig.7. The topographical datasets of the Necropoli delle Grotte path and tombs under the tree crown cover, integrating regional map*

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