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UNDERGROUND HERITAGE DOCUMENTATION: THE CASE STUDY OF GROTTA ZINZULUSA IN CASTRO (LECCE-ITALY) / Tanduo, B.; Chiabrando, F.; Coluccia, L.; Auriemma, R.. - In: THE INTERNATIONAL ARCHIVES OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES. - ISSN 1682-1777. - ELETTRONICO. - XLVIII-M-2-2023:(2023), pp. 1527-1534. [10.5194/isprs-archives-XLVIII-M-2-2023-1527-2023]

Availability:
This version is available at: 11583/2979784 since: 2023-07-03T10:55:11Z

Publisher:
Copernicus Publications

Published
DOI:10.5194/isprs-archives-XLVIII-M-2-2023-1527-2023

UNDERGROUND HERITAGE DOCUMENTATION: THE CASE STUDY OF GROTTA ZINZULUSA IN CASTRO (LECCE-ITALY)

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KEY WORDS: Underground Heritage, Cultural Heritage Documentation, 3D survey, MMSs, SLAM technology, data integration, digital archaeology.

ABSTRACT:

3D documentation of the Underground Built Heritage (UBH) is always fundamental for knowledge, management, conservation, and enhancement of cultural heritage, but the challenges involved in documenting this kind of site are many and various, With the aim of providing an accurate and reliable representation of the surveyed area without employing time-consuming processes, Mobile Mapping Systems (MMSs) based on SLAM (Simultaneous Localization And Mapping) technology have now the potential to overcome these challenges, proving to be a useful alternative to traditional surveying techniques. The underground site of Grotta Zinzulusa in Castro (LE), Italy, is an anchialine cave system difficult to access and document due to its narrow passages, large rooms, and poor illumination. Within this case study, the effectiveness of using an MMS approach, employing the STONEX® X120^{GO} *SLAM Laser Scanner* system, to document the cave system and integrates the data with those obtained from other traditional geomatics techniques, such as UAS (Uncrewed Aerial System) and TLS (Terrestrial Laser Scanning) surveys, has been proved. The study aims to define the best practices and operational methodologies for enhancing the speediness, usability, and cost-effectiveness of using MMSs in underground settings for 3D documentation of heritage sites to provide metrically correct and accurate products for researchers, scientists, and the wider public.

1. INTRODUCTION

Underground heritage, among the CH (cultural heritage) context, represents the most largely unexplored, inaccessible, not even documented, and under-utilized scenario. Although underground sites constitute a unique resource, this lack of knowledge affects different research fields (from history to geomatics, archaeology, and geology), limiting their full exploitation and valorization.

The 3D documentation of CH represents the first fundamental operation in the process of knowledge, management, conservation, and enhancement of the heritage itself. With a view to a multi- and inter-disciplinary approach, each step of the knowledge process should be defined a priori, with the aim of obtaining the maximum participation and cooperation of the experts involved (Tobiasz et al., 2019). Furthermore, 3D data acquisition allows both to obtain metrically correct and accurate products for researchers and scientists and provides access to this difficult-to-reach heritage also to the wide public, using virtual tours and immersive technologies. In defining the survey project, it is essential to consider the different aspects that can influence the documentation process: the accessibility of the places, the accuracy required for the final products, the time available for the data acquisition phase, and the cost related to the entire process (Georgopoulos et al., 2017).

Documenting the underground heritage is even more challenging. In complex and large underground sites, the selected documenting approach must ensure quick environment mapping speeding up the acquisition phase: agile, low-cost, and easy-to-use sensors should be preferable in order to overcome the lack of accessibility of these places and to collect relevant amount of data avoiding time-consuming procedures (Di Stefano et al., 2021).

Therefore, it is crucial to consider the potential use of MMSs (Mobile Mapping Systems) in underground heritage mapping; the ease of use, speed of acquisition, and low cost of the instrumentation all work to make this method competitive with more traditional techniques.

1.1 Grotta Zinzulusa: the underground case study

The documented area is represented by the internal spaces of Grotta Zinzulusa and its external relevance concerning the walkway leading to the entrance of the cave and the stretch of nearby coast (Figure 1).

Grotta Zinzulusa is a natural anchialin coastal cave located in Castro (LE), Italy. With its 160 m of length, it presents all the features that make it a challenging scenario to access and document: scarce accessibility, different levels in depth, poor and variable illumination, narrow passages, long corridors, large rooms, and flooded or partly flooded areas.

Due to its historical background and its geological conformation, the cave system represents an important site for several disciplines: it is an extraordinary intensely populated hotspot of underground biodiversity (26 aquatic and 40 terrestrial rare and delicate species), has a wide variety of paleontological finds, sediments, stalactites and stalagmites, and presents traces of human attendance from prehistoric ages, as shown by the numerous palethnological finds (Cardini, 1959; Blanc, 1961).

During July 1957 the cave has been explored by experts from the "*Centro Speleologico Meridionale*" and "*Gruppo Speleologico Salentino di Maglie*" and a first survey has been carried out (Figure 2). Starting from this year, Grotta Zinzulusa has been opened to the wide public, also gaining fame as an important touristic site: on average it is visited by 100,000 tourists per year, with peaks of 3,500 visitors per day.

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This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1527-2023

Figure 1. Panoramic view of the cave entrance, Grotta Zinzulusa, Castro (LE)

The part open to the public are the first 150 meters of the cave, while the remaining part, partly flooded, is not accessible due to the considerable importance of its biodiversity.

In 1999, the Karst Waters Institute (KWI) included the cave in the list of the 10 world karst systems at greatest risk, of which it is necessary to ensure adequate protection.

During the summer 2023, some archaeological digging operation will begin: first, the freshwater pond called “La Conca” (Area A) and located next to the entrance will be investigated, in order to recover a submerged archaeological record; finally, some studies will be carried out in the part coinciding with the final section of the walkway called “Duomo” (Area B), characterized by numerous signs engraved on the rock walls referable to letters or inscriptions dating back to various historical periods.

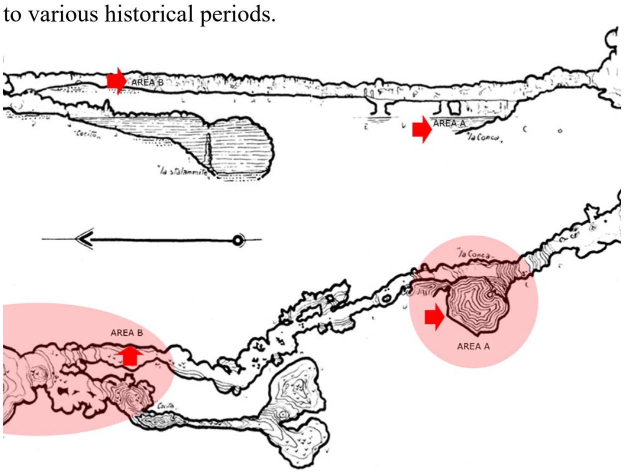


Figure 2. Part of the *“Digging authorization”* showing plan and section made in 1957 with the two areas of interest (Parenzan, 1983)

2. MATERIALS AND METHODS

The survey campaign has been carried out over a couple of days in October 2022. The survey activities have been planned to collect both outdoor aerial and indoor terrestrial data, for improving the knowledge of the geometrical consistency of the cave and the seashore portion of the bay surrounding the entrance of the cave. For the complete documentation of the area a multi-scale UAS survey has been performed to collect data of the outdoor context; for the indoor environment and the cave entry both a TLS and an MMS approach has been adopted.

2.1 UAV data acquisition and processing

A DJI Phantom 4 Pro platform, equipped with a 1” CMOS camera, was employed for the UAV survey (Table 1).

	Resolution [pix]	Focal length [mm]	Pixel size [µm]
	5472 x 3648	8,8 mm	2,4

Table 1. DJI Phantom 4 Pro camera main technical specifications.

The entire area of the bay has been overflown during two different flights with an elevation of around 50 m and a GSD (Ground Sample Distance) of 1,36 cm.

Thanks to the 3-axis gimbal system of the Phantom 4 Pro camera, we have been able to acquire both nadiral and obliques images. A total of 523 images has been collected, with a lateral overlapping of 60% and longitudinal of 80% (Figure 3).

Figure 3. UAS nadiral images acquisition scheme.

For the Bundle Block adjustment and the accuracy evaluation of the final photogrammetric products the 3D coordinates of 10 markers were measured using a Leica GS10 GNSS (Global Navigation Satellite System) receiver, employing an NRTK (Network Real-Time Kinematic) approach using the active connection of the platform to a GNSS permanent network (HxGM smartnet service from Hexagon). All the points coordinates are expressed in the UTM WGS 84 - 34N reference system and geoidic elevation, computed using the ondulation provided by the Italian Geographic Military Institute (IGM). Also, a GNSS network of 3 vertexes has been measured using static observation (1h acquisition time, sample rate of 30 sec). The GNSS network has then been adjusted using the data of the GNSS Apulia permanet stations of Patù, Meledugno and Avetrana.

The photogrammetric data were processed using the SfM (Structure from Motion) software Agisoft Metashape following the standard workflow to obtain 3D models and orthoimages of the area (Figure 4).

Within this dataset, 6 of the measured points were considered as GCPs (Ground Control Points) and 4 were employed as CPs (Check Points). The main results of the processing are reported in Table 2.

N° of images	N° of GCPs	N° of CPs	RMS Error [cm]	
			GCPs	CPs
523	6	4	0,3	1,9

Table 2. RMS error for GCPs and CPs.

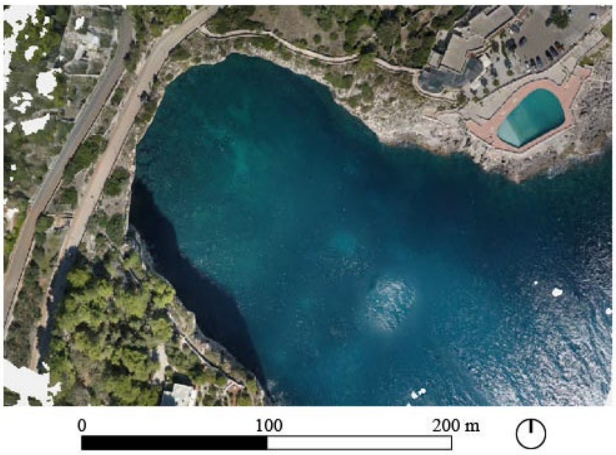


Figure 4. UAS orthoimage of the shore portion outside Grotta Zinzulusa.

2.2 TLS data acquisition and processing

As regarding the indoor environment of the cave, first a documentation with traditional survey techniques has been carried out: a reference topographic network using a Total Station has been set up starting from the GNSS measured vertexes and then a TLS survey has been carried out.

A total of 46 static scans were acquired (Figure 5), covering all the cave length, using a FARO Focus^{3D} X330 system (Table 3).

Figure 5. TLS scans acquisition scheme (red dots show the scans position)

	Range [m]	0,6 - 330
	Scanning point frequency [points/s]	~976,000
	Ranging error [mm]	2
	FOV	300°x360°

Table 3. FARO Focus^{3D} X330 laser scanner main technical specifications.

As it’s well known in the Geomatic field, the TLS survey is a consolidated documentation approach that lead to great results in terms of accuracy and data quality; on the other hand, in this particular case study it has required a lot of time for the acquisition phase, and, due to the conformation of the spaces, a lot of effort in detecting the best acquisition scheme that permits to cover the entire length of the cave with a reasonable overlap value between consecutive scans (Figure 6).

Figure 6. Tight and narrow indoor spaces of Grotta Zinzulusa.

The processing phase was conducted through the Cyclone REGISTER 360 software by Leica, using a two-step registration approach: first, a cloud-to-cloud registration, optimized with ICP (Iterative Closest Point) algorithm, was performed obtaining a mean residual of 0,7 cm; then, all the scans were georeferenced based on the target measured using the topographic approach, using the markers measured by the employed total station Trimble SX12. The mean target residual obtained is 1,2 cm.

The TLS dataset, has been used as ground truth to evaluate the accuracy and the quality of the acquired MMS point clouds.

2.3 MMS data acquisition and processing

For the purpose of this research, the most effort has been dedicated to the MMS data acquisition and processing. In the last few years in the sphere of Cultural Heritage documentation, as well as in other domains, the use of low-cost solutions and rapid mapping approaches has been deeply investigated and implemented (Barba et al., 2021, Di Filippo et al., 2018, Rodríguez-Gonzálvez et al., 2017).

As a generic definition nowadays an MMS can be described as a mobile survey platform based on SLAM (Simultaneous Localization And Mapping) technology that can concurrently map the environment and localize itself within the generated 3D map. An MMS could integrate both mapping sensors, like LiDAR (Light Detection And Range) scanner, spherical or semi-spherical cameras, and navigation/positioning sensors such as GNSS (Global Navigation Satellite System) receiver and IMU (Inertial Measurements Unit) platform (Puente et al, 2013). In this way, the system can provide in real time 3D point clouds obtained by the automatic scan-to-scan registration with an accuracy of a few centimeters.

Within this particular case study, finding the best documentation approach was especially challenging and considering the use of MMSs is crucial both to overcome some issues related to the conformation of the spaces and to exploit and evaluate the full potentiality of these kind of sensors.

Regarding the issues, it has to be said as breafly reported before that the indoor environment of the cave presents: i) a huge complexity in its geometry, switching many times between narrow corridors, large “rooms”, tight stairs, and flooded areas; ii) an overall lack of accessibility, occurred mainly in a series of narrow passages and corridors between “La Conca” and the final areas of the “Duomo”, in a repetition of flooded or partly flooded areas, and in the presence of some tight stairs that connect the different level in height of the cave; iii) a general poor and variable illumination, with only a few spots well enlightened.

https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1527-2023

In a such large and complex underground site, agile and user-friendly sensors should be preferable in order to collect a relevant amount of data avoiding time-consuming procedures. Within these purposes, portable mapping systems allow: i) to reduce and speed up the acquisition phase, allowing us to acquire the entire geometry of the cave in less than twenty minutes and thus reducing the need to spend a lot of time in delicate environments and therefore the possibility of causing problems both for the presence of delicate species of fauna and for the alteration of the humidity levels of the environments; ii) to better overcome the lack of accessibility and to better manage with the spatial complexity of the spaces, since these systems are characterized by an high portability, handling and easiness of use; iii) to collect a large amount of reliable, fast, and ready-to-use 3D data, containing both geometric and radiometric informations, without the necessity of a topographic support; iv) to definitely cut the costs related to the entire survey process (acquisition phase and post processing of the data).

The tested MMS is the STONEX® X120^{GO} *SLAM Laser Scanner* system (Figure 7), a last generation hand-held system equipped with an Hesai XT16 LiDAR sensor and three 5MP cameras, capable of synchronously obtaining texture information and producing coloured point clouds and partial panoramic images. The main specifications of this system are reported in Table 4.

Figure 7. The STONEX® X120^{GO} *SLAM Laser Scanner* (https://www.stonex.it/project/x120go-slam-laser-scanner).

	LiDAR (Hesai XT16)	Cameras 3 (5 MP each)
Range	0.5 m – 120 m	-
Scanning point frequency	320,000 pts/s	-
Relative accuracy	6 mm	-
FOV	360° x 270°	200° x 100°

Table 4. STONEX® X120^{GO} *SLAM Laser Scanner* main technical specification.

Five different acquisition paths (Table 5) have been performed: both the indoor of the cave and the outdoor environment related to the cliff have been documented, trying to acquire a redundant number of overlapping scans. As regard the indoor scenario (cave) we tried to perform paths that allow us to acquire all the geometric features of the spaces, so not only the pathway open to the public (main walkway) has been considered but also every inlet and indentation of the rock have been documented and mapped. For the outdoor context (cliff) all the walkway leading from the parking area to the entrance of the cave has been considered in the acquisition path.

As it's well known, performing a loop closure path is the best solution when dealing with these kind of mapping systems: the closure of the loop of scans enables the distribution of the incremental residual error accumulated with the subsequent scan-to-scan matching (Hess et al., 2016, Tucci et al., 2018). On the other hand, also ensure the acquisition of not too large, heavy and difficult-to-manage datasets must be a priority: for this reason, the acquisition time should not be over 10-15 minutes. Following both these two considerations, it was feasible to complete a loop closure path only in two of the five acquisitions: the conformation of the cave and the shore (both in terms of length and accessibility) meant that the documentation path lasted not less than 10-15 minutes, so it was not always possible to go back to the starting point to close the scans.

	Scenario	Acquisition time [min]	Path length [m]	Loop closure
Dataset 1	cave	~ 20	396,80	yes
Dataset 2	cave	~ 10	203,45	no
Dataset 3	cliff	~ 10	253,50	no
Dataset 4	cave	~ 10	280,35	yes
Dataset 5	cliff	~ 10	247,85	no

Table 5. Main characteristics of the five acquisition paths.

The post-processing phase has been carried out using a two-step approach: first, an initial optimization was performed within the dedicated software GO*post* by STONEX® following the standard workflow; finally, all the MMS point clouds have been georeferenced in the UTM WGS 84 - 34N coordinate system.

As regard the first phase, an optimization of the acquired point cloud has been performed: the software allows to recompute the IMU trajectory in a more accurate way, and consequently to re-map the documented spaces. Simultaneously, a process of filtering (i.e. pedestrian removing), denoising and thinning has been conducted, as well as the point cloud coloring and an overall point cloud optimization. Within this phase, it was also possible to process the data acquired by the three cameras: a de-distortion operation procedure has been accomplished for all the images, and they have been consequently used to stitch panorama images (Figure 8).

All the five datasets have been processed with the same parameters.

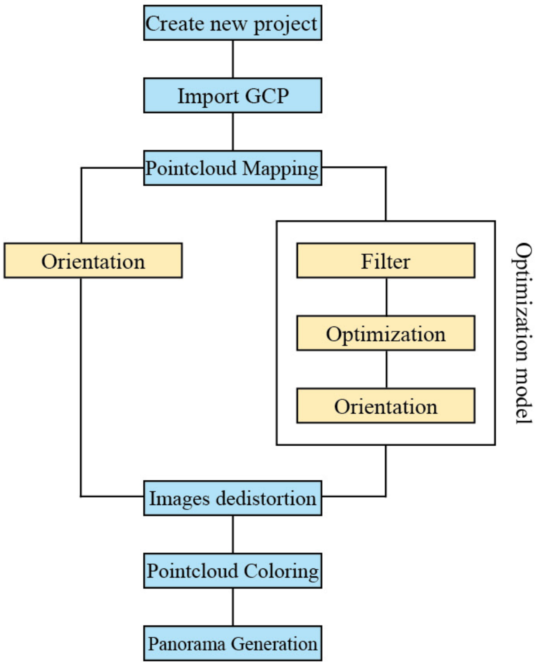


Figure 8. The followed workflow of the post-processing phase, as suggested by the STONEX® X120^{GO} *SLAM Laser Scanner* user guide[4]. *The Orientation phase has been conducted throw the Cyclone REGISTER 360 software.

Then all the point clouds have been georeferenced in the common reference system (UTM WGS 84 - 34N): unfortunately, it was not possible to recognize topographic targets within the MMS point clouds, so an ICP (Iterative Closest Point) registration has been performed, using the TLS data as a ground reference for the indoor environment and the UAV data for the outdoor context. The main results of the post-processing phase are reported in Table 6 and the point cloud derived from the elaboration of the first dataset is depicted in Figure 9.

	N° of points	Elaboration time [h]	ICP RMS error [cm]
Dataset 1	44 479 860	1:57	2,7
Dataset 2	34 846 190	1:34	4,0
Dataset 3	17 670 607	1:02	3,9
Dataset 4	33 963 261	1:30	3,2
Dataset 5	20 500 901	1:04	4,5

Table 6. Principal results regarding the post-processing phase, the ICP registration has been conducted throw the Cyclone REGISTER 360 software.

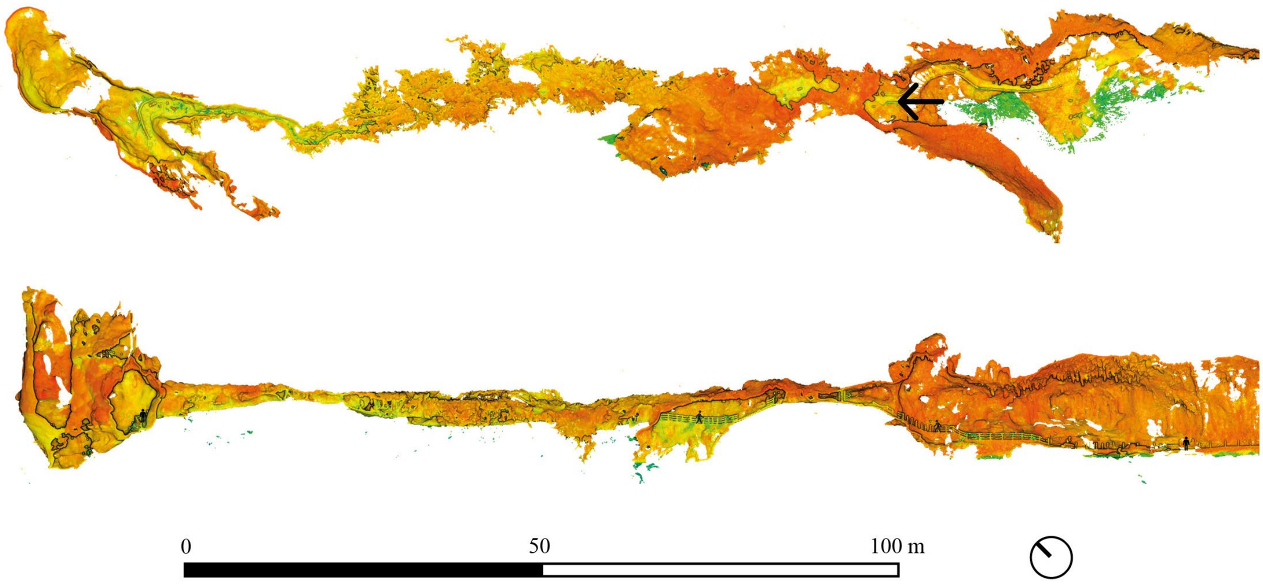


Figure 9. Plan and section of the obtained STONEX® X120^{GO} *SLAM Laser Scanner* point cloud (Dataset 1). The point cloud is displayed with the Intensity value as point colour and the black arrow states the cave entrance.

3. EVALUATION OF THE MMS DATASETS

The dense point clouds obtained with the STONEX® X120^{GO} system have been used for estimating its mapping capability in different indoor underground areas and outdoor spaces, using the TLS data as ground truth. The acquired datasets have been evaluated considering: i) metric accuracy; ii) completeness of the point cloud; iii) quality of the geometrical reconstruction.

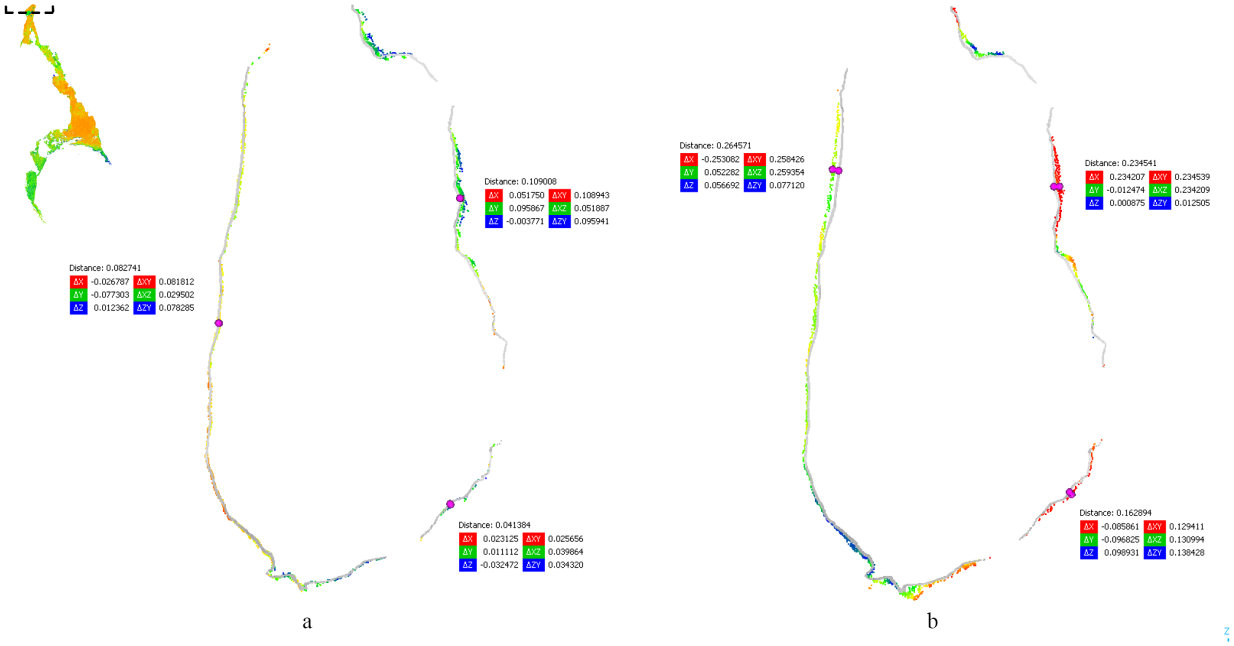
Since the main purpose was to evaluate the STONEX® X120^{GO} performances in an underground complex asset, only the indoor underground area has been taken into consideration in this analysis (Dataset 1, 2 and 4).

At a first step, the completeness of the reconstruction has been assessed: both the first and the second point clouds cover the entire length of the cave, the last one, however, concerns only the first 100 m of the indoor environment.

Then, a comparison along transversal sections has been performed, to roughly detect the greater discrepancies with respect to the reference TLS point cloud.

Both for Dataset 1 and Dataset 2 three different sections have been extracted and analysed. 3D distances between the reference and the compared data have been punctually computed: as we expected, since in the case of Dataset 2 we didn't perform a loop closure path this point cloud presents and incremental error along the length of the path, starting from 2-4 cm in the starting point and ending with distance values up to 15-25 cm in the final area of the "Duomo" (Figure 10b). Sections of the Dataset 1 show discrepancies up to 1-2 cm in the cave entrance and up to 8 cm at the end of the cave (Figure 10a).

Also, the first point cloud is the most complete in terms of space coverage since the scanning path comprehends every inlet of the rock in the cave indoor environment and not only the touristic pathway.



a

b

Figure 10. Visual comparison along section in the “Duomo” of the reference TLS point cloud with the MMS Dataset 1 (a) and Dataset 2 (b).

For these reasons Dataset 1 was chosen to deepen the tests with further and more extended analysis.

Defined the best acquisition path and so the most suitable dataset, additional tests have been carried out within the post-processing phase: the same raw point cloud has been re-processed five different times, changing from 1 to 5 the “Stability” parameter.

This parameter is referred to the degree of variability of the scanning scene: for indoor environment is preferable to use the Stability parameter set as 5, 3 or 4 has to be used for mixed environment, 1 or 2 for outdoor and widely various scenarios (STONEX® X120^{GO} *SLAM Laser Scanner* User Manual).

In this particular case we were dealing with an indoor space, but extremely complex and articulated: since the Stability it’s not an objective parameter, most of the choice is left to the operators’ judgment and experience, and for this kind of scenarios setting a priori the “best” value of this parameter is therefore quite challenging.

The major differences between the five tested workflows substantially concern the processing time of the point clouds: the recomputing of the IMU trajectory is performed at different speeds and degrees of accuracy, and the consequent re-mapping of the spaces documented by the LiDAR sensor goes through different levels of filtering and optimization. That leads to a variation in the number of points of the obtained datasets, manifestation of a different average thickness of the point clouds (Table 7).

For each dataset, a C2C (Cloud to Cloud) distance analysis has been carried out, to evaluate the deviations of the analysed cloud using the root mean square error (RMSe) (Figure 11). Also, the values of surface density have been computed to assess the dataset's completeness and quality, and the noise level has been locally analyzed using the “roughness” mathematical algorithm.

All the analysis have been conducted through the open-source platform CloudCompare (CC). The main results are reported in Table 8.

Dataset	Elaboration time [h]	N° of points	Mean thickness [cm]
Stability 1	3:23	31 390 607	2
Stability 2	2:27	32 057 290	2
Stability 3	1:49	33 963 261	4
Stability 4	1:30	34 173 952	5
Stability 5	1:11	34 669 026	7

Table 7. Main evidence regarding the post processing phase changing the Stability parameter. With low values of Stability the processing time significantly increases, the final optimized point cloud undergoes a more aggressive filtering and thinning operations and therefore has a lower number of total points.

	C2C [cm]		Density* [points/m^2]	Roughness*
	Mean	Std. Dev.		
Stability 1	6,0	10,8	16 900	0,0022
Stability 2	6,8	12,5	18 450	0,0023
Stability 3	6,4	11,4	23 336	0,0025
Stability 4	7,2	13,9	25 129	0,0025
Stability 5	8,2	14,6	26 828	0,0026

Table 8. Results of the analysis performed. * The values of density and roughness are referred to a sphere with a radius of 2 cm.

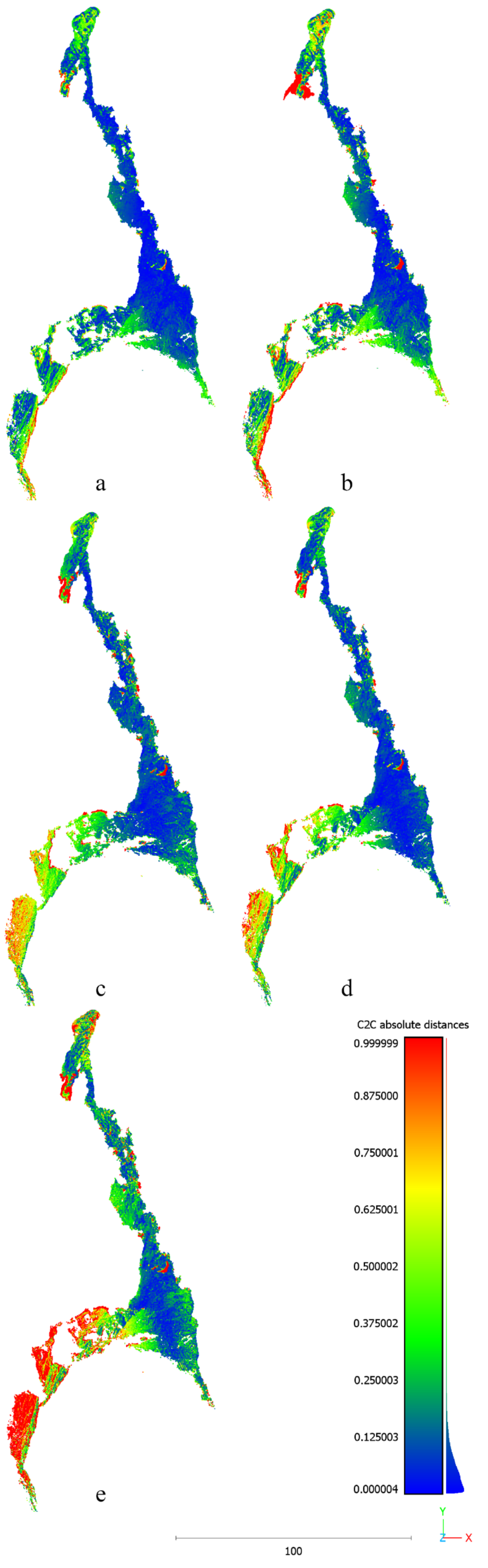


Figure 11. C2C comparison between the Dataset 1 (STONEX® X120^{GO} *SLAM Laser Scanner*) and the LiDAR data (FARO Focus^{3D} X330). The (a) image shows the evaluation of the point cloud computed with Stability value set at 1, the (e) is referred to the one processed with the Stability value set at 5.

4. DISCUSSION AND CONCLUSIONS

The essential goal when dealing with MMSs is to estimate the uncertainty of the resulting 3D data considering the evaluation of the overall accuracy, especially in terms of 3D space reconstruction and drift errors affecting the trajectory according to the different environmental conditions.

The results show how the MMS approach can now be competitive with more traditional survey methods: the analysis performed within all the datasets allows us to define best practices and rules regarding the survey process.

Regarding the acquisition phase, as shown by comparing the transversal sections extracted from Dataset 1 and Dataset 2, it’s always better to perform a loop closure path. Also, maintaining a constant walking speed is fundamental to obtaining a homogeneous result in terms of surface density (even if the density value of MMS point clouds remains far below, thus regarding TLS datasets). Regarding the level of noise, it is generally influenced by the distance of the system from the acquired points and by the operator's capability to maintain a stable attitude, avoiding sudden changes of direction: the not-so-wide indoor environment and some precautions in speed and stability during the paths, allow us to obtained low values of roughness (smaller than 3 mm).

Regarding the post-processing phase, it has been proved how the different degrees in accuracy when recomputing the MMS trajectory deeply influenced the final results. The processing time highly improves whenever we decide to perform a more efficient reprocessing, but the C2C comparison shows that the obtained point clouds present a higher overall level of accuracy with respect to thus reprocessed in less time with lower attention to the trajectory recomputing.

In general, using the MMS approach applied to the archaeological survey of underground sites can consistently speed up the survey operations without neglecting the gathered data's quality and reliability. Implementing these procedures also provides better conditions for the operators involved due to the reduction of the overall acquisition time. Critical aspects of applying this methodology are mainly related to the level of detail needed for the surveyed area: it has been shown that MMS datasets are suitable, in such a large complex site, for a drawing scale not larger than 1:100/1:200, even if considering the local level the accuracy and the quality of the obtained point clouds highly improve.

Besides having an high portability of the system, also the produced datasets present an high level of manageability and sharing: MMS final products are usually easy to manage and to integrate with thus derived from other Geomatics techniques (Figure 11).

Figure 11. Example of data integration (UAS and MMS point clouds).

Thanks to the achieved topographic network, a multi-sensor and multi-scale approach been adopted to collect data concerning the cave system, displaying and analyzing them together in the same reference system (Mandelli et al., 2017; Teppati Losè et al., 2021).
Integration of experimental Geomatics techniques, like the use of MMSs implementing SLAM technology, with those already widely established, such as UAS and TLS survey, is consequently intended to find an operational methodology that allows enhancing the speediness, usability, and cost-effectiveness qualities of the MMSs approach, defining best practices for exploiting mobile systems in underground settings.
Many variables have to be considered and many precautions have to be taken when facing to obtain complete and accurate 3D documentation of the hidden underground heritage in a rapid, agile, and low-cost way using mobile mapping technologies. Therefore, it is possible to state that data acquired from MMSs can be successfully used as a fast-surveying technique to achieve 3D models of the difficult-to-reach Underground Cultural Heritage, and in this specific case, the models will allow the actors involved in the archaeological studies to improve the knowledge of the Zinzulusa cave.

ACKNOWLEDGEMENTS

The authors would like to thank the STONEX® team for providing the X120^{GO} *SLAM Laser Scanner* system for the survey; in particular, thanks to Gianluca Renghini, Chiara Ponti and Umberto Montedoro for their presence in Grotta Zinzulusa and for their support within the acquisition phase of the Mobile Mapping System datasets. Many thanks to Giuseppe Furfaro for supplying us with the necessary instrumentation to complete the survey and for his substantial support in the acquisition of topographical, GNSS and LiDAR data. Thanks to Emiliano Peluso for the UAS acquisition support. Many thanks to Alessio Calantropio for his presence and help during the acquisition phase, and to Luigi Coluccia for sharing with us his great knowledge of the studied area, and for handling the organizational parts of the mission.

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