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Introducing Interdisciplinary Innovative Techniques for Mapping Karstic Caves

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The purpose of this research is to describe a methodology for the generation of a complete 3D model of a karstic cave. We applied this methodology at two different karstic geo-environments in Cephalonia Island (Melissani and Drogarati show caves) and despite this fact, this particular methodology was successfully applied for both missions. We incorporated close-range remote sensing techniques and equipment including a Terrestrial Laser Scanner (TLS), a Handheld Laser Scanner (HLS), and an Unmanned Aerial System (UAS), maximizing the quality and precision of the 3D results. The high precision of the combined methodology is based on the use of multi-allocated control points which are established either on the surface or beneath it, throughout the area of each cave. All the coordinate measurements were calculated by using RTK-GNSS (for the surface points) and total station equipment (for the subsurface points) which allowed us to create a multi-source, high accurate, geo-rectified, dense, and above all the aforementioned, unified point cloud for each geomorphological cavity. The evolution of technology and the development of 3D space, such as computer vision, modelling, printing etc. in three-dimension, covered the needs of constructing 3D geological models for mapping, analysing and studying the earth's surface in a modern way. Nowadays, 3D modelling is applicable in every geological field such as in palaeontology, petrology, tectonics (Barreau *et al.*, 2022; Apopei *et al.*, 2021; Mavroulis *et al.*, 2022 and references within) among others. Moreover, the 3D representation of morphological structures, such as steep cliffs, gorges, karstic landforms, and caves, gives us nowadays the opportunity to study geomorphology in depth, in terms of monitoring geomorphic changes over time, erosion detection and quantification, risk management, and geo-heritage prominence and conservation (Spyrou *et al.*, 2022). Specifically in caves, a karst environment with exquisite beauty and an attraction for naturalists and tourists, 3D mapping, analysis, quality, and quantity are now essential components for their systematic study (Konsolaki *et al.*, 2020). The use of state-of-the-art equipment provide the means to map and visualize the walls, roof, and floor of a cave, including cave deposits, by constructing high quality topography inside the cave and above it as well. Cave systems are very complex environments and variant from each other, dependent on the bioclimatic conditions, formation processes, and hydro-chemical reactions taking place in a region. Therefore, the methodology to be applied, regarding the mapping and generation of the 3D model, varies and should be adapted according to the morphology of the cave. Regarding our research, there are two main parts concerning (i) the underground cavity and (ii) the open surface above, where several point clouds were constructed with two different methods. The first one is based on millions of direct measurements (TLS, HLS) whilst the second one is indirectly induced by photogrammetric processing (UAS images).

Melissani Cave is an underground lake that is situated in the northwestern part of the coastal settlement of Karavomilos (Cephalonia). The natural entrance, which is located at a collapsed doline above the cave, was created according to historical sources after a strong earthquake. A large opening (about 30m long and 20m wide) was formed at the ceiling of the underlying cavity and a spectacular subsurface lake was revealed. Continuous rockfalls resulted the concentration of large amounts of debris at several parts in the cave, forming shallow areas and emerged piles within the lake. The latter were used for placing the steady surveying equipment, whilst a boat was used for the mobile one. Specifically, the methodology included (i) terrestrial laser scanning from 6 predetermined bases on the debris pile, the artificial pier, and on a platform at the edge of the doline, constructing several point clouds for most of the floor, roof, and walls of the cave with a spatial resolution of 5mm, and (ii) handheld laser scanning by boating around the walls, where additional data acquisition was necessary either for increasing the resolution or for surveying hidden passages and hard-to-reach areas. A total of 20 control points were placed on the cavity walls where their true coordinates were measured with the total station along with 5 control points that were established on flat surfaces around the cave. The dataset was completed with a point cloud which was extracted after the photogrammetric processing of a series of georectified images (401 photos) of the open surface. They were acquired by a DJI Phantom 4 RTK, which carries an onboard multi-frequency multi-constellation GNSS receiver, allowing the adoption of the NRTK approach (Panagiotopoulou *et al.*, 2020) for the data acquisition and processing to ensure the highest accuracy of the results. The acquired point clouds were then pre-processed, cleaned, and merged, leading to the final product, a high spatial resolution cloud layer consisting of 629 million points which can be further processed and visualized in three dimensions (Fig. 1).

In contrast to Melissani, **Drogarati Cave** is a horizontal cavern, situated 1km east of the settlement of Haliotata (Cephalonia) and it consists of two main parts; (i) a collapsed doline which represents the natural entrance, and (ii) a very large chamber with dimensions of 63m*47m, divided into two sections, with 7m elevation difference, due to boulders that were detached from its roof, creating a barrier. The methodology followed, varied from the one previously described regarding handheld laser scanning, since lots of hidden passages behind columns characterize the geomorphology of this cave, making the mobile data acquisition technique more efficient than TLS which in this case portrayed as supplementary. The latter was accomplished by establishing 5 successive bases in clear line of sight with a traverse approach.

Figure 1: The complete 3D model of Melissani Cave with the surface above it.

In total, 23 control points were established and measured throughout the cave, of which 15 were placed on the cavity walls and 8 spread across the floor. A high density 841-million-point cloud of Drogarati Cave led to the production of a 3D model, after merging the individual point clouds with the one that was extracted after surveying the open surface above the cave with the UAS and the photogrammetric processing that followed (Fig. 2).

Figure 2: The complete 3D model of Drogarati Cave with the surface above it.

In conclusion, the implementation of the described methodology at the study of the caves provides an additional tool for identifying the high-risk areas, aiming to increase the safety of the visitors. At both cases, digital measurements of the rock thickness between the roof of the underground karstic structures and the open-surface topography, as well as mapping the rock discontinuities in high detail, can be presented with very high accuracy.

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