Sparus II AUV as a Sensor Suite for Underwater Archaeology: Falconera Cave Experiments

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***Abstract*—The present work tries to improve the topographical and prospective methodology applied to underwater archaeology, as well as the different technical tools used in the study of submerged caves, using as a experimental site one of the most contaminated and dangerous submerged caves in Europe called Falconera Cave (Sitges, Barcelona). The results have shown that the application of traditional procedures together with the use of the Sparus II Autonomous Underwater Vehicle (AUV) equipped with a multibeam echosounder represent the best technical solution for georeferencing in this submerged archaeological contexts.**

***Index Terms*—underwater archaeology, mapping**

I. Introduction

Since these first archaeological studies in submerged cavities in the 19th century [1], the investigations have focused mainly on topographic studies [2], aimed at locating the sites in relation to the classic topographies carried out manually in the caves [3]. Usually, this type of research has not focused on correctly georeferencing the topographies of the cavities, making more difficult their study and localization of possible openings from the outside.

Nowadays, most of the underwater cave topographies are made by caving sport divers, using a basic topographic method, based on the measurement of different points on the guide line and the triangulation of the walls and ceiling of the cave with respect to those points (Fig. 1). This information helps to understand, in a preliminary way, the geographical location both inside and outside the cave of the submerged archaeological site. However, the objectives of sport divers and their work methodology are far from archaeological interests, since accurate archaeological records are essential for the latter. The impossibility of using any type of GPS device means that we only know the entrance coordinate to the cave, making it necessary to create a rigorous cartographic map from that single coordinate. To date, the use of underwater mapping devices has been especially useful, making measurements more rigorous and dives safer. Unfortunately, the Falconera cave (Sitges, Barcelona) is considered one of the most polluted underwater water tables in the world, which makes an exhaustive topographic record difficult due to the lack of visibility.

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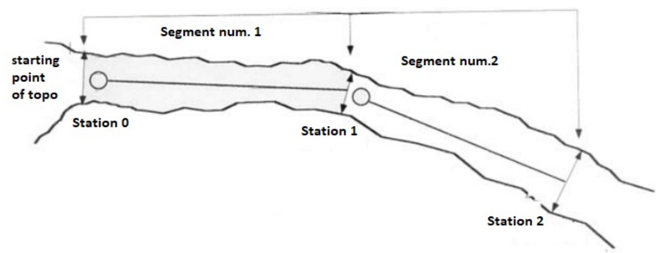

Fig. 1. Example on manual topographical measurements by recording the distance and orientation between different stations on the guide line, and the station distance to the walls at left/right/top/bottom.

In this proposal, the Sparus II Autonomous Underwater Vehicle (AUV) [4] equipped with a multibeam echosounder mounted on a pan and tilt unit, was introduced to the Falconera cave by a team of divers to obtain its complete topography for future archaeological surveys.

The paper is organized as follows, Section II describes the Falconera cave and its archaeological interest. Section III presents the Sparus II AUV as a sensor rig and its operation by the divers. Section IV describes the data obtained, the resulting map and its archaeological significance. Finally, in Section V, we present the conclusions.

II. Falconera cave

The Falconera Cave (UTM 31N, X: 407154, Y: 4567011), is a cave located in the Garraf Massif, near the harbor of Garraf (Barcelona, Spain). The cave is mainly underwater and there is a fresh water current that originates in the underground phreatic levels that causes the existence of various upwellings, both inside and outside of it, originating the so-called underground river of the Falconera. This river is supplied by the filtration of the waters of the torrent of the Falconera and the rainwater, causing an outlet pressure that is counteracted by the pressure exerted by the strong waves that hit the rocky shores [5].

When underwater speleological explorations in the cavity began, a series of very basic topographies of the cavity had

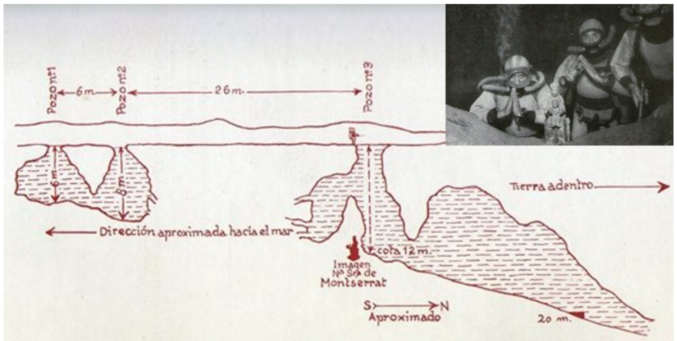

Fig. 2. Section of the Falconera cave draw by Ballester and Admetlla in 1953 with a corresponding picture of the dive.

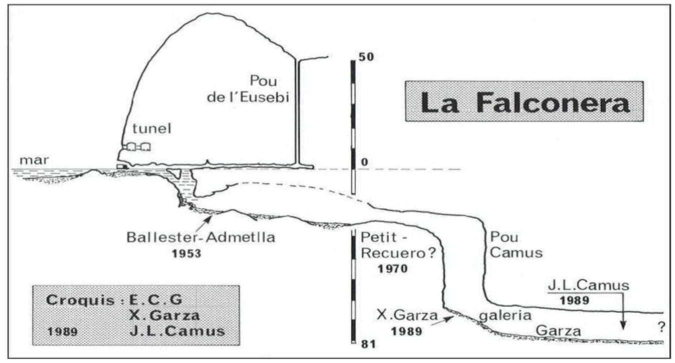

Fig. 3. Section of the Falconera cave draw by Garza in 1989.

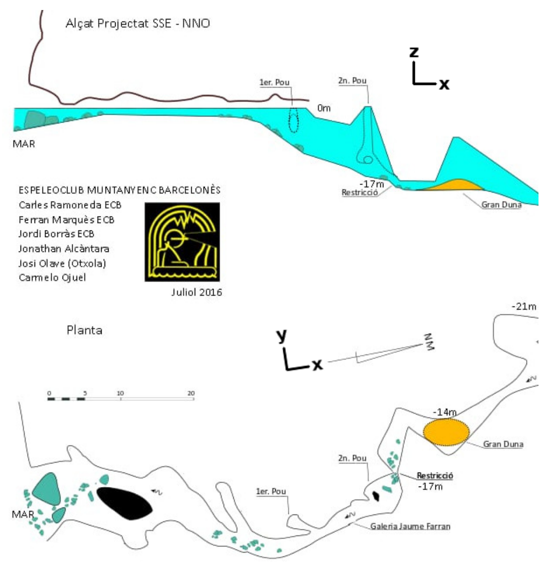

Fig. 4. The Falconera cave map obtained by the ECMB divers in 2016. The xyz axis correspond to north, west, down. The big sand dune that moves depending on the currents can be observed in yellow, rocks in blue-gray and the water level (only in the elevation view) in light blue.

already been carried out to help understand it from a technical point of view, but not a scientific one. As a summary, we will list different key dates in the topographic advance of the cavity [6]–[9]. In 1953, thanks to the use of an autonomous diving suit, the caver Antonio Ballester and the *Centro de Recuperación y de Investigaciones Submarinas (CRIS)* diver Eduard Admetlla made the first underwater dive, reaching a depth of 20 meters (Fig. 2). In 1961, the *Grup d'Escalada i Espeleologia de Badalona (GEEB)* Ramon Canela and others made another dive, but it was not until 1970 that, promoted by the *Federación Española de Actividades Subacuáticas (FEDAS)*, "Operation Garraf-70" where the team formed by E. Petit and R. Recuero claimed to have reached 350 meters away inside the cave and at a depth of 40 meters.

In 1988, the French caver-diver Jean Louis Camus and Javier Garza made a first reconnaissance and despite the fact that the visibility was barely 2 meters, they realized the magnitude of the gallery. Shortly after, Garza installed 145 meters of guide wire so that Camus, with more sophisticated means, could go further. This dive took place on January 14th 1989 and contrary to what was known up to that moment from the Petit-Recuero topography, the gallery closes completely at 200 meters. At this point, a huge shaft about 20 meters in diameter is the vertical continuation of the cavity. Later, Garza manages to reach a depth of 66 meters. But it wasn't until April 3rd 1989, when Camus, with a mixture of gases and oxygen to perform decompression, began a dive that would last 180 minutes, following the gallery previously explored by Garza to the bottom of the well. Once you get there, a ramp appears that becomes flat, reaching a depth of 81 meters (Fig. 3). Once there, the lack of visibility and a soil formed by muddy sediment made him give up and return to the surface.

Subsequently, new dives have been made, but they have not reached the importance of the one in 1989 and basically the search for the "mysterious" Petit-Recuero gallery has continued, without any results. It was not until 2016 when the *Speleo Club Muntanyenc Barcelonés (ECMB)* cave diving team composed by Carles Ramoneda, Ferran Marqués Artero, Jordi Borrás, Jonathan Alcantara, Carmelo Ojuel and Josi Olave (Otxola) that made a new updated topography of the first 140 meters of the cavity (Fig. 4).

Thanks to this recent topography, we were able to analyze and study the possible archaeological prospecting areas in the entrance galleries of the cavity. The study carried out by the EMCB not only indicated the approximate position within the cavity of the first restriction, located at -17 meters, but also indicated the existence of a large sand dune next to the restriction. Depending on whether the cave is loading or unloading the water accumulated in the internal phreatic levels of the mountain, the sand dune hinders the passage to the Great Hall of Ballester-Admetlla, which is very important because it considerably modifies the morphology of the cave by displacing tons of sand deposited inside the cave.

Currently, the water is highly contaminated and dangerous due to leaks from the now closed metropolitan dump of Vall de Joan, in the town of Gavà, located at 5 km in a straight line. This closed landfill is located in a natural area of the Garraf Massif, in which under its green surface lay more than 26.7 million tons of garbage ferment and where mountains

Fig. 5. Example of pollution expelled by Falconera cave after heavy rain.

of leached waste accumulate between 80 and 100 meters in height. This leaching and the filtration of rainwater causes the Falconera cave to expel into the sea, in times of maximum rainfall, a large amount of polluting wastewater (Fig. 5). Such an environmental disaster causes the Falconera cavity to be an infamous place for diving, full of suspended organic material to which is added the halocline caused by the lack of visibility when fresh water mixes with sea salt, percolation and the lash of the waves at the entrance of the cavity [10], [11].

The archaeological study in the Falconera cave aims to demonstrate that the fresh water in this cavity was used as a water supply point for the surrounding prehistoric villages. The different paleo-climatic studies [12] indicate that around 8000 years ago, the sea was 12 meters below the current level. As a consequence, the paleo-phreatic level of the fresh water within the cave must have been the same as the sea level, increasing considerably until it overflowed in times of high rainfall when the waters of the Falconera stream flowed into the cave. For this reason, and following the hypothesis of the previous study [13], any archaeological remains, both ceramic and lithic, that can be preserved in the interior should be buried under the layer of sand in the so-called ”Jaume Farran Gallery”.

Due to the low visibility and the possible contamination of the water, the experiment consisted in introducing a diver-guided AUV equipped with sonars to obtain as much data as possible in the minimum diving time. Moreover, a period without heavy rains and calm sea was required to operate safely inside the cave as well as its entrance.

III. Sparus II AUV

The Sparus II AUV was equipped with an Imagenex DeltaT Multibeam Echosounder mounted on a pan and tilt unit. The multibeam measurements cover a 120° region, that coupled with the tilt movement in the range $[-90°, +90°]$ provides us with data of a third of the surrounding sphere in each complete tilt movement.

Since complete autonomy in underwater caves has not yet been achieved to the best of the authors knowledge, for the mapping of the Falconera cave the vehicle was driven by the divers themselves. Because of that, thrusters were disabled to

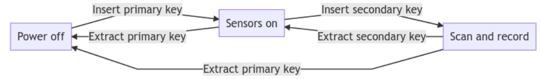

Fig. 6. State diagram for the magnetic keys usage.

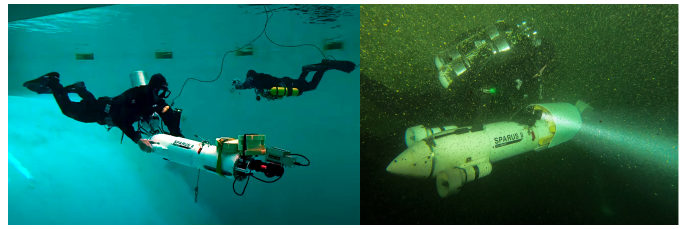

Fig. 7. *(left)* Training of the divers in the CIRS water tank where Sparus II AUV is mounted with the multibeam and the pan and tilt unit. *(right)* Real conditions in the Falconera cave during the experiments.

not interfere with guidance and the vehicle was trimmed to be completely neutrally buoyant.

The divers were instructed to move centered in the cavity and with slow movements. Moreover, they also were instructed that every 10 meters they should do a complete turn around a static point to obtain more useful data.

Sparus II AUV has a magnetic primary key for powering on/off the vehicle on the right side of the central vertical thruster. Once the key is plugged-in, the vehicle boots and already starts all the navigation sensors and waits for user input. An extra secondary magnetic key was added on the left side of the central vertical thruster to enable this communication with the divers. Once the second key is inserted, the vehicle starts the tilt movement while also starts recording all the sensor data (Fig. 6).

Previous to mapping the real cave, the divers were trained at the Underwater Robotics Research Center (CIRS) water tank to ensure that the system was working properly and the divers had no problem maneuvering it (Fig. 7).

IV. Results

Several dives with different strategies were planed to maximize data collection (Table I). In the first dive, after each full tilt movement, the multibeam was chaining its maximum range between three different values (5, 10, 20) to ensure proper data collection. The diver was moving in a continuous path to cover the whole length of the cave until the first restriction, which was completely covered by the sand dune.

On the second dive, the diver was stopping at different spots spaced every 3 to 5 meters. When stopped, he would turn on the scanning and do a complete turn on the spot and then disable the scanning again to move to the next spot. This should provide a lidar-like dataset, but due to misunderstandings with the divers, the dataset was not correctly obtained.

After the first two dives, the data was rapidly analyzed on the boat to see which ranges were obtaining measurements with less noise by composing the multibeam measurement over the dead-reckoning trajectory (Fig. 8). This resulted on a third

TABLE I
EXPERIMENTS CONDUCTED ON THE FALCONERA CAVE.

Dive	Range (m)	Strategy
1	5/10/20	Continuous movement
2	5/10/20	Static points
3	5	Continuous movement

dive with a fixed range of 5 meters and a continuous movement of the diver.

The final map was constructed *a posteriori* by dividing the trajectory into different submaps obtained by composing the dead-reckoning trajectory with the sonar measurements. Those submaps where registered together using the Iterative Closest Point (ICP) algorithm to correct the drift between re-observed regions (Fig. 9).

The resulting point cloud indicates the possibility of spatial knowledge of a cavity in conditions of poor or no visibility thanks to the use of sonar sensors. In this case, it allows to accurately measure the dimensions of the "Jaume Farran Gallery" (from the entrance to the first restriction of the Falconera cave). Moreover, it shows a significant error in the manual topography carried out by the ECMB team.

The obtained point cloud shows us a sector of the cave with regular tube-shaped walls without any type of shelter or rocks where a possible archaeological deposit could be sheltered and preserved, and without additional bifurcations in the gallery, which does not affect the entrance flow and fresh water outlet [14]. The bottom of the cavity has a uniform sand blanket that increases in thickness with increasing depth.

This information will indicate the most viable area for carrying out a future archaeological survey, minimizing risks and maximizing the dive time. This point cloud data will be used to create a volumetric model of the cavity and exported to a Geographical Information System (GIS) that can be consulted by experts, which will allow to make precise measurements.

V. CONCLUSIONS

The use of the multibeam system with a dead-reckoning navigation composed by Inertial Measurement Unit (IMU), pressure sensor and Doppler Velocity Logger (DVL) guarantees the reliability and rigor of the measurements necessary for underwater archaeology. These can be easily exported to a GIS to contextualize the study of possible archaeological sites submerged in their geological and historical context, which will create a precedent for prospective action in underwater archaeology in submerged cavities. In addition, it guarantees the safety of caving divers, reducing immersion time inside the cavity while obtaining more useful data. Furthermore, we can extrapolate this working model to any cavity that has problems to achieve a correct topography due to lack or no visibility underwater.

From a robotics point of view, the real data obtained from an underwater cave, can help the development of future online SLAM algorithms that ensure a proper localization of the vehicle and can enable high-level behaviours like complete autonomous exploration of underwater cavities.

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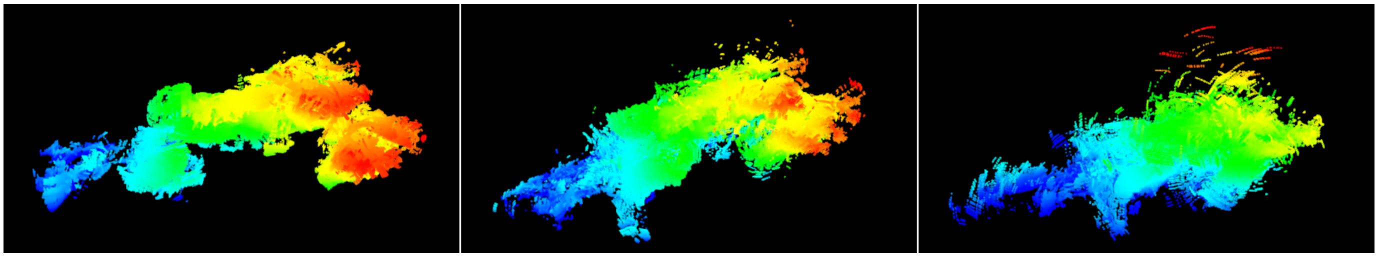

Fig. 8. Fast maps computed on the boat for ranges 5m, 10m and 20m. The leftmost (5m range) is the one that presents less echoes and outliers.

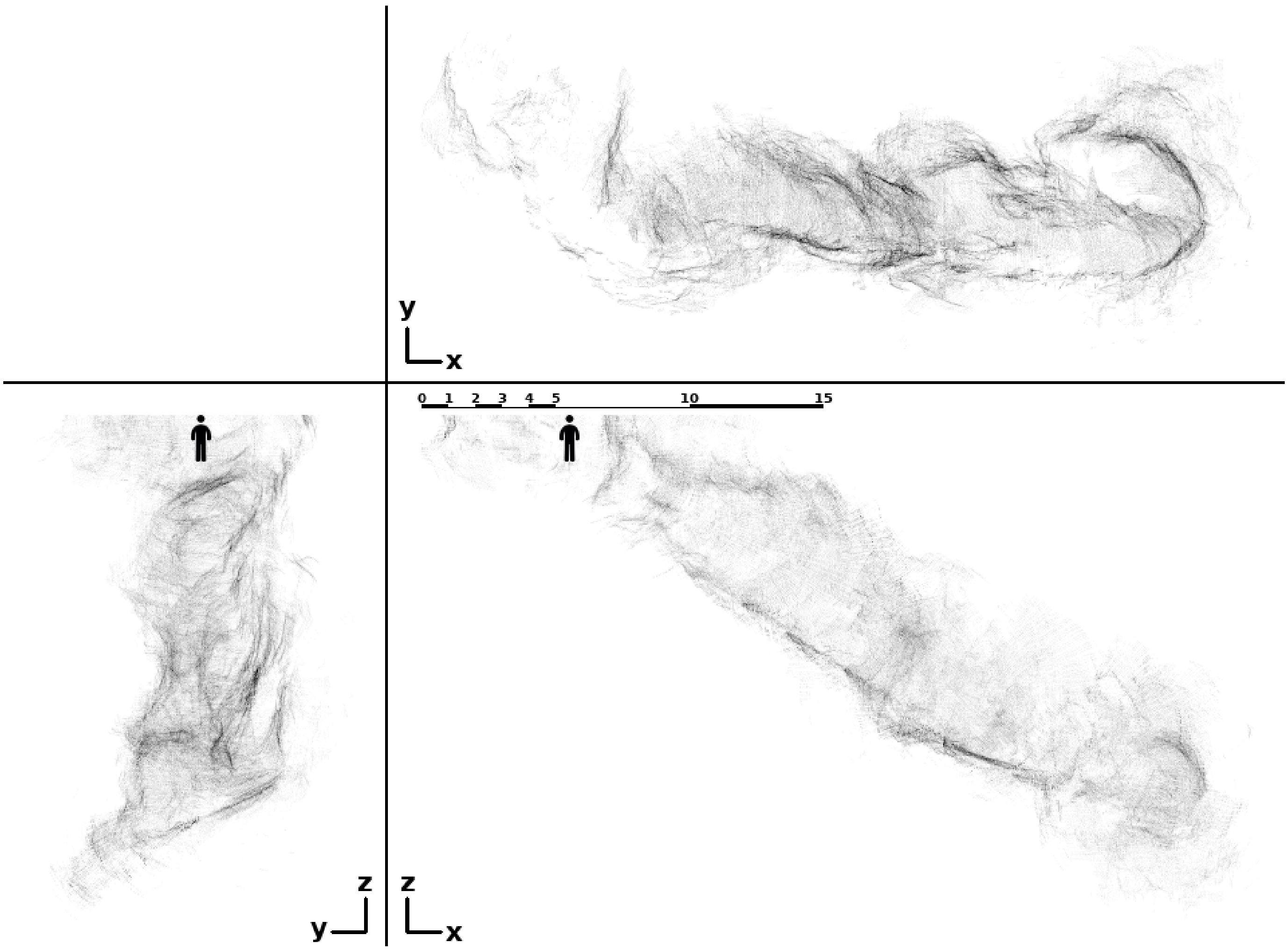

Fig. 9. Projections of the final point cloud reconstruction of the Falconera cave with a human figure for scale reference (0.05 m/pixel). The xyz axis correspond to north, west, down.