Thesaurus Project: Design of New Autonomous Underwater Vehicles for Documentation and Protection of Underwater Archaeological Sites

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Abstract. The Thesaurus Project, funded by the Regione Toscana, combines humanistic and technological research aiming at developing a new generation of cooperating Autonomous Underwater Vehicles and at documenting ancient and modern Tuscany shipwrecks. Technological research will allow performing an archaeological exploration mission through the use of a swarm of autonomous, smart and self-organizing underwater vehicles. Using acoustic communications, these vehicles will be able to exchange each other data related to the state of the exploration and then to adapt their behavior to improve the survey. The archival research and archaeological survey aim at collecting all reports related to the underwater evidences and the events of sinking occurred in the sea of Tuscany. The collected data will be organized in a specific database suitably modeled.

Keywords: Autonomous Underwater Vehicles, Robot Cooperation, Tuscany, Wrecks, Etruscan, Roman, Medieval, Modern.

1 Protecting and Preserving the Tuscan Underwater CH

Italian laws strictly forbid misappropriation of underwater archaeological finds, while belong to public property. Nevertheless amateur divers deliberately infringe such rules and many important shipwrecks on the Tuscan coasts have been ransacked so far down to 50m. In the Eighties the Underwater Unit was launched at the Regional

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Board of the Ministry of Cultural Heritage and Environmental Conservation, whose personnel excavated many wrecks. A thick web of archaeological areas turned out, many of which were partly ransacked but still identifiable. Then a straightforward database was built up from archival, archaeological and oral sources, in order to collect and to look-through the numerous set of facts. That preliminary umbrella filing was as sundry as useful for characterizing the dispersal of wrecks, single artifacts, and even conjectured relics, despite it was still weak in site-location due to the later spread of GPS coordinates use. If actually amateur divers cannot go deeper than -50m, other human actions can cause severe injuries, as this is the case of dragnets: in the mid of the Nineties the underwater Marseille company Comex explored the so-called 'Elba Sud' wreck that is almost 200m deep and 12 miles far from the island towards Montecristo. That investigation unearthed the ruins of the cargo made of Roman Spanish amphoras that were dispersed through an area of 25x4m. The Comex also brought to light the steamship 'Polluce', owned by Raffaele Rubattino and sunk in 1841, which now lies at -103m not far from Porto Azzurro. Later on, during the 'Archeomar' action promoted by the Ministry, the Comex Company found a 178m deep shipwreck near the Gorgona Island: two of the nine dolia that were part of the cargo had been previously picked up by drag boats. Together with photomosaic and stereoscopics, the find of deeper shipwrecks with their undamaged cargoes plays a pivotal role in the archaeological and historical research of ancient routes and trades.

2 AUV Design

The aim of the project Thesaurus is to develop a modular system of cooperative Autonomous Underwater Vehicles (AUV) in order to perform navigation, exploration and surveillance of underwater archaeological sites at maximum depth of more than 300meters. Three different underwater vehicles cooperating in a single swarm will be developed and a surface boat with support tasks will be also available. All vehicles will have a similar mechanical design but each one will be equipped with a different sensor layout in order to perform complementary tasks. The master vehicle will be equipped with an inertial navigation system, a magnetometer, a pressure/depth sensor and a DVL (Doppler Velocity Log), that will be used – through data fusion procedures – to estimate the position of the vehicle. The other two vehicles instead will be equipped with specific sensor so to acquire measures under the coordination of

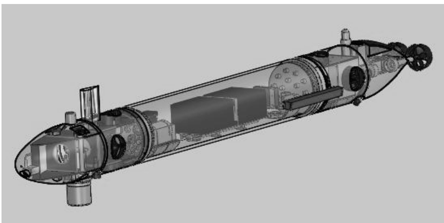

Fig. 1. Design of the Tifone AUV (particular): main propellers and lateral thrusters

the master vehicle thanks to acoustic communication. In particular the first one will be equipped with side scan sonars in order to map large-scale sea bottom. The last one will be dedicated to computer vision task (see section 3) with a particular hardware optimized for visual 3D reconstruction, detection and classification of the sea bottom. The cooperative navigation and localization algorithm implemented on the swarm is described in a previous work [1]: the boat absolute position is known through GPS, the relative distances between swarm elements are measured by acoustic modems, additional measurements provided by inertial, magnetometer and depth sensors are further improved using data fusion procedures with the determinant contribution on the speed/position DVL sensor installed on the master vehicle. Since each vehicle differs only in terms of sensors layout and payload, the naval and the electromechanical design is based on a common vehicle class named Tifone (see fig. 1). Tifone is designed with a torpedo like shape, commonly adopted by many existing AUV [2] [3] [4] [5]. Considering encumbrances of payloads and specifications of the project, the main dimensions of the vehicle will result in a total length of 2 meters and an external diameter of 300-320mm. The hull is composed by a main watertight fiberglass cylinder with two end cups which is enclosing two battery packages, a computer governing the vehicle vital functions like navigation and communications and a computer dedicated to store and process the scientific data. Data are provided by a variety of sensors, which are located in the specific slot of the vehicle appendixes. Being the outfitting of each sensor set interchangeable, each of the three vehicles can be easily specialized for the specific task assigned.

Since mission will range from 8 to 12 hours, good autonomy is required. In order to maximize the capacity of the energy storage system Li-Po (Lithium-Polymer) batteries – which have higher energy capacities [6] [7], respect to other kind of accumulators – will be used. Also Li-Po technology drastically reduces the risk of fire/explosion usually associated to traditional Li-ion batteries. The chosen layout involves the use of two packs of batteries for a total power of 3840 kWh which is enough according specifications, even considering a performance degradation of the 10% due to aging or to incomplete/fast recharge. In addition, backup batteries with limited power will be installed in order to assure minimal communication and localization features in case of brake-down of the main power system. The propulsion (fig. 2) will be realized by a system of actuators composed by two main propellers and four thrusters (vertical and lateral), so that linear motions along x, y, z directions, and pitch and yaw rotations will be directly controlled. This layout was chosen in order to privilege maneuverability and hovering performances of the vehicle.

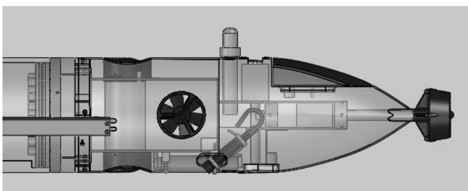

Fig. 2. Design of the Tifone AUV (particular): main propellers and lateral thrusters

3 Optical and Acoustic Sensory Data Analysis

As already said, two vehicles of the swarm will be equipped with specific sensors to be able to gather data (optical and acoustic) of the underwater environment. The hardware set comprises a pair of cameras, two led illuminators, a laser stripe profiler for the vision vehicle and a side scan sonar for the acoustic one.

The captured data maps must be preliminary processed in order to enhance the signal component and to reduce the noise. Moreover, the physical parameters of the medium (water turbidity, partial light polarization, density and temperature variations) in which the light propagation occurs introduce geometrical distortions in the acquired optical images. Image properties must be restored by calibration and rectification operations.

The two main task addressed by computer vision in the Thesaurus project will be multi-view geometric 3D reconstruction and image-based object recognition [8]. Geometric scene analysis will be carried out at first directly on-board through a combination of Simultaneous Localization And Mapping (SLAM) [9] and active rectification [10]. SLAM techniques are designed to estimate simultaneously a sparse 3D reconstruction of the environment and the time-varying relative position of the vehicles from a video sequence. Each frame of the sequence will be analyzed so to detect salient point of interest (PoI). Using specific local descriptor – that characterize the appearance of the local patch around the PoI – the system will be able to establish point matches between subsequent images. Then geometrical constrain based on the found matches will be exploited to recover the three-dimensional scene and the point of view relative to each single image frame. In addition, by merging the movement information obtained with the inertial sensors available on the AUV and the SLAM estimates, it's possible to archive higher precision on the trajectory assessment. On the other hand, using the laser stripe profiler and the active rectification approach, the system will be able to reconstruct in 3D small regions of interest with high accuracy. Active rectification relies on the observation of the deformation of a light pattern while it interacts with the scene. While the AUV (and the laser projector mounted on it) moves, different sections of the sea bottom will be illuminated and a sequence of 3D laser profile can be recorded. Then, knowing the AUV movements, it is possible to merge all the single profiles in a unique 3D model with high resolution. Moreover the active rectification approach is able to reconstruct texture-less objects, as clay pottery without painting or inscription. Also the image-based recognition will be carried out on board during the mission. The recognition task, mainly addressed to identify object of interest (i.e. historical artefacts), will operate both in two-dimensional space – analyzing the recorded images – and in three-dimensional space – the reconstructed 3D environment computed with SLAM and active rectification. In particular, a method for 2D object detection that is robust w.r.t. partial occlusions [11] will be developed, so as to work properly in the underwater archaeological context where only artefact fragments surfacing from the seabed are usually visible. 3D recognition of archaeological artefacts will be based on the use of 3D model fitting and validation techniques, thus achieving viewpoint independence. At first the system will search for simple geometric structure, such as plane or quadrics. In case of positive detections, the system will try to fit more complex shape – i.e. pre-acquired 3D model of amphorae or anchors – so to recognize human-made artefacts. At the end of the mission the whole video footage will be downloaded from the AUV – together with the estimated data – and completely re-analyzed with different algorithms characterized by high computational load but capable to return finer output results.

The acoustic device transmits sound impulses through the water and captures the backscattering echoes from the seafloor. This produces 2D high resolution seafloor acoustic maps. As in the optical case, the acoustic data are firstly processed during the survey, by means of fast real-time algorithms, to immediately detect potentially interesting sites; then, by off-line operating, the data are processed in a more accurate way, using more complex procedures. Side scan map formation is affected by typical geometrical distortions due to the capture of the slanted backscattered echoes. To restore the environment geometrical properties, the sonar maps must be processed by Slant/Ground range transformation algorithms. The preliminary processed maps need to be manipulated in order to obtain large scale maps (mosaics) by stitching single maps together. Areas of the seafloor containing handmade objects exhibit interesting properties such as the presence of geometrical curves (e.g. amphora's neck contour) or repetitions of textural patterns. The mosaic maps can be processed to detect, recognize and classify the above mentioned features, by means of appropriate computer vision algorithms. At the end, sonar maps can be manipulated to infer the seabed height map. By evaluating the luminosity gradients in the image, the elevation map is estimated applying Shape From Shading algorithms to the sonograms.

4 Robot Cooperation and Coordination in the Project Thesaurus

A fundamental aspect of multi robots coordination is related to the communication possibilities. Since optical or, in any case, electromagnetic underwater communication is limited to extremely short ranges by the strongly attenuating nature of the transmitting medium (salt water), a key role is played by acoustic communication. Unfortunately, this also implies severe communication constraints imposed by the band-limited and range-limited physical nature of the underwater acoustic communication channel [12] [13]. Transmission range and channel capacity may suffer dramatic changes as a consequence of variations in oceanographic conditions, and specifically in the sound speed in the medium. The project Thesaurus addresses all these problems at two different levels, (a) developing an appropriate acoustic network infrastructure that is able to face, both at physical and at network level, the uncertainties of the acoustic communication, and (b) devising and implementing distributed cooperative algorithms able to face the limitations due to the communications, making the AUVs able to adapt their behavior to the variation of the acoustic channel.

From the point of view of the AUV distributed decision making, in the Thesaurus context, a cooperative algorithm has been designed based on the idea of potential games. According to this framework, each AUV is modelled as a self-interested

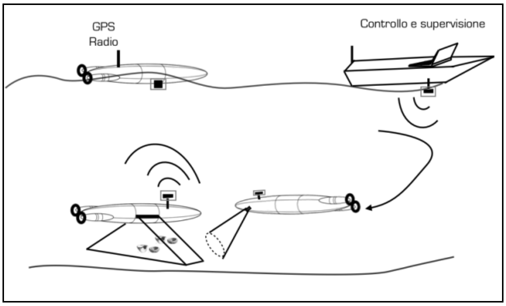

Fig. 3. Archaeological exploration using a team of AUVs. The agents explore the area in cooperation. When one of the robots detects something that may be of interest, it can alert the others so that the entire group can participate to a deeper exploration and classification.

agent, with a utility function dependant both on the acoustic communication performance (e.g. Signal-to-Noise Ratio) and on the completion of the archaeological exploration. From an architectural perspective this maps into the implementation of a mission supervisor capable of interpreting and generating messages to the other network nodes (AUVs), and to give commands to the vehicle native guidance, navigation and control (GNC) system, which is the sole responsible of the low-level execution of the commands. Figure 3 conceptually depicts the idea of AUVs cooperation within the Thesaurus Project. In this case, one of the agents stays on surface to get GPS and to geo-localize the other vehicles, which remain underwater to continue the archaeological exploration. The AUVs communicate continuously both among themselves to coordinate the mission actions, and with a remote station (located on a boat in the picture) that can interact with the vehicle to modify or add new missions.

5 The Archaeological and Archival Research

The aim of the archaeological research is twofold: the collection of edited data and the re-examination of the most relevant wrecks. As for the first, the collection of bibliographical and archival records has been made easier by the Soprintendenza per i Beni Archeologici della Toscana, which has shared its database with the Thesaurus Project. This database contains basic information not only about ancient wrecks but also about isolated and decontextualized items. So far, it has been possible to add some other data to it, reaching 400 records, of which about 55 wrecks (known or alleged). All the data collected have been georeferenced thanks to a specific GIS platform and inserted into a suitably modeled database. As for the re-examination of some ancient wrecks, the work, started in 2011, is still in progress. The research has been planned according to different criteria: chronological, geographical and thematic. A study of all the Etruscan records has been undertaken since any accurate research has never been done on such topic till up now. The same can be said about the late antique wrecks and finds. Referring to Roman times, the selected contexts are the harbor area of Porto Azzurro (Isola d’Elba), where the remains of at least three wrecks have been mixed with a long-life harbor dump, and some wrecks from various spots at Isola d'Elba. These wrecks were published some decades ago, often in an only preliminary way. In particular, the Procchio wreck, dated to the II century AD, carried some stamped sulphur blocks along with the usual amphorae cargo. The Chiessi wreck, unfortunately almost completely spoiled by clandestine digs, was one of the biggest wrecks in the Mediterranean sea and one of the few carrying Ramón 25 amphorae. The Sant'Andrea A and B wrecks instead carried Dressel 1 amphorae, which are characterized by many epigraphic data and are being restudied. Moreover, the 'dolia' wrecks, used to transport unbottled wine and quite frequent in the Tuscan sea, are being re-examined: the most relevant are the Meloria B wreck (near Livorno), the Punta del Nasuto wreck (Isola d'Elba) and the Gorgona Sud wreck, almost 180m deep.

Besides the study of ancient wrecks, we have started an investigation of more recent shipwrecks, dating from medieval age to the World War II. For this time-frame the data gathered are indeed quite fragmented, given that the Soprintendenza's database includes only occasional records about medieval and modern wrecks. The investigation therefore has been planned in a different way: considering the broad time-frame it has been chosen to carry out a bibliographic and historical survey, complemented by an archival search, which has permitted to select, during the centuries, several news of shipwrecks, which, however, only rarely correspond to documented wrecks. Despite their wide variability, shipwrecks information can be catalogued in three typologies. The first typology includes wrecks well attested in the bibliographical or archival sources: the most famous case is the Pollux steamship, sunk in 1841 and recovered close to the Elba island. The second typology consists of shipwrecks documented only by their partial remains: for instance, close to the Elba island, two eighteenth-century wrecks, conventionally named Procchio B and Scoglietto (Portoferraio). These samples, well documented by the Soprintendenza's archive, lack the documentary sources thus their historical context remains unclear. The last typology is known only through documentary material: for instance, a ship loaded of ancient marbles, sunk in 1550 close to the Piombino cape. These cases have been chosen in consideration of their good documentation, despite the absence of archaeological evidence.

6 Thesaurus Information System

The Thesaurus information system will manage both sensor data, acquired during seabed explorations, and historical and archival, archaeological and documentary data resulting from humanistic researches. The system is able to acquire and properly integrate all the provided information. In more detail, the Thesaurus informative system has been designed aiming at storing data obtained by historical and archival sources, explorative missions and elaborations of acquired data. Moreover it allows to perform search and retrieval operations exploiting database queries, to run data-mining algorithms, to display data as multimedia sources and to navigate the scenes explored by AUV through the 3D environment and objects reconstructions. In order to manage geo-referenced data a relational database spatial enabled has been realized. For the historical and archival data, due to their complexity and heterogeneity, a native XML database has been chosen in order to obtain a better flexibility for managing the information. By comparing with pre-existing models, the Thesaurus system has resulted more granular and specific.

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