A Feedback Scheme for Missions Managing in Underwater Archeology

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Abstract: In the present paper, the formalization of a practical methodology for the cooperation, at various levels, of UUV and human operators in the exploration of underwater archaeological sites is presented. The approach proposed here is part of the work done in the framework of the EU Research Project VENUS in order to redesign the procedures for gathering archaeological data by exploiting beneficially the potential of cooperation between human operators and robotics devices, such as ROVs. The main innovative aspect of the proposed procedure is the on-line construction of mosaic 2D maps, which is used to implement a logic feedback loop in governing the survey process.

Keywords: Underwater Archaeology, Marine Technology, Data Gathering, Submarine Robotics..

1. INTRODUCTION

The exploration of submerged sites is a challenging and difficult task which deserves primary interest in underwater archeology. The main issue in the archaeological investigation is the extraction, in a non invasive way, of as much information as possible from a site with minimal expenditure of time and resources. In general, this is done by taking photos and measurements of objects and terrain, which are then used to construct representations of the site in form of local maps. In the underwater environment, this activity was traditionally performed by divers, limiting the operations to shallow waters (less than 30m deep in most cases). Manned and unmanned vehicles started to be consistently employed in the exploration of high depth sites in the lasts 20 years (see [1]-[3], [16], [20]), in situations that do not allow the use of traditional diving techniques. In general, the use of such technologies is very demanding in terms of economical, material and human resources (see [17], [18], [21], [22]) and not always the archeological relevance of a site motivates their use. Nevertheless, also minor sites can contain valuable information and their investigation could greatly benefit of the use of modern, advanced techniques. Therefore, there is a strong interest in the archaeological community for the development of methods and procedures that combine advanced and traditional technologies in order to maximize the efficacy of both, while limiting costs.

Our aim, here, is to present an approach for obtaining results in the direction mentioned above by employing low-cost equipments and by exploiting the possibilities of cooperation, at various levels, between man and Unmanned Underwater Vehicles (UUVs). In doing this, we summarize results already partially presented in [4], [5] and we will add new material concerning the construction of mosaic maps and their use in archaeological surveys.

The basic problem to deal with in the exploration of submerged sites is that of collecting a large amount of spatially dense, high quality data, in form of optical and acoustic images, in the harsh underwater environment. In the approach we propose, cooperation between man and UUV is formalized in such a way to make possible, for the archaeologists, to guide the data gathering process in a logic feedback fashion. This is obtained by employing an ROV for data gathering and by processing on-line part of the data in such a way to construct in (almost) real-time 2D mosaic maps of the explored area. Such maps represent the fed back information to be used for controlling the process. This, in addition, gives us the possibility to redesign the standard manual procedures for structuring the site according to a general design-to-automation principle. In this way, it is possible to exploit fully the potential of robotics devices such as ROVs and of automatic data processing, first, in collecting large quantity of spatially dense, correlated optical and acoustic images and, then, in extracting information in form of 2D or 3D, GIS compatible maps. The use of the methodology we propose can substantially increase the efficiency of the data gathering procedure in shallow waters, where divers could still operate, while extending it without additional costs to a depth of more than 100m.

Experimental work done by the authors in the framework of the European Project VENUS and of other research activities is used to illustrate the proposed methodology and the results obtained during specific missions.

The paper is organized as follows. In Section II, the general problem concerning the collection of data in underwater archaeological surveys is discussed and the proposed procedure is schematically presented. In particular, its feedback loop architecture, based on on-line construction of 2D photomosaic maps, is illustrated. In Section III, the proposed procedures for automatic data collection and processing are illustrated with reference to experimental work. In Section IV, conclusions are presented.

2. DATA GATHERING PROCEDURES

In traditional marine archaeological surveys, data gathering procedures involve divers for taking photos and measures, whose correlation and interpretation is facilitated by structuring the area of interest by means of frames and landmarks. This, as well as the manual collection of data, is a hard and invasive work that put divers and equipment at risk.

In order to accomplish the job in a satisfactory and exhaustive way, investigators have to return repeatedly to the same location and the whole process is cumbersome and time consuming. In particular, since data taken during each dive can be examined only after the end of the dive itself, the acquisition process can be governed by the archaeologists (i.e. the end-users) only in an open loop fashion.

This situation can be modified and improved by designing and developing procedures and best practices for collecting data from underwater archaeological sites, which exploit robotic vehicles and automatic devices under the supervision of archaeologists and engineers possibly in cooperation, under some circumstances, with divers [6]-[9]. Essentially, robotic vehicles are used to carry cameras, video-cameras and acoustic sensors in order to collect optical and acoustic images of the site. These are transmitted to a supply vessel and, together with navigation data, they are automatically processed in real time and then, possibly, post-processed in order to improve results and extract additional information.

In the proposed methodology, the introduction of one or more robotic vehicles in substitutions of divers is intended to speed up the exploration of the site, while allowing for possible on-line rescheduling of the mission or parameters adjusting (see [11], [20], [22]). This is obtained by implementing a sort of logic feedback loop, based on the possibility of constructing on-line, with respect to the whole process, a 2D map of the explored site by means of photomosaicing techniques. The choice to limit the use of highly expensive, equipments, implies trading off between accuracy and low-cost viability, keeping quality and efficiency at a satisfactory level from the end users point of view. The fact of making the output of the survey process, namely the map, available - although in a preliminary form - in real time is one of the key advantages gained by collecting data (in this case, photos and video frames) in automatic way by means of sensors installed on robotic vehicles like ROVs. The 2D maps represent the fed back information that can be used for governing the data acquisition process in a closed loop fashion. This information is crucial for implementing a feedback loop and it cannot be obtained using traditional techniques based on manual data acquisition. The feedback mechanism allows the archaeologists to modify some of the survey parameters (e.g. area coverage, point of sight, data density and so on) during operation, saving time and reducing costs substantially.

Other important advantages of using robotic vehicles for collecting data are, obviously, the fact of avoiding the risks of diving and the possibility of working at high depth for long time. At the same time, the quantity and the spatial density of data are greatly increased. Navigation data, in addition, establish spatial correlation between photos which have not been taken sequentially and allow to construct geo-referenced maps of photogrammetric quality, augmented by information acquired by means of sonar, sub-bottom profiler and magnetometer, if available. Maps obtained in this way can be accurate enough to allow a satisfactory virtual reconstruction of the site at specified levels of precision.

Roughly, the major activities that define the work in marine archaeological surveys include: 1-*pre-analysis of the area*, 2-*goal definition*, 3-*mission design*, 4-*local survey*, 5-*documentation*, 6-*excavation*, 7-*post-analysis and final documentation*. Our interest here is concentrated on the phases which precede the excavation. Figure 1 depicts the activities flow diagram in case ROVs and automatic data gathering procedures are involved in the process.

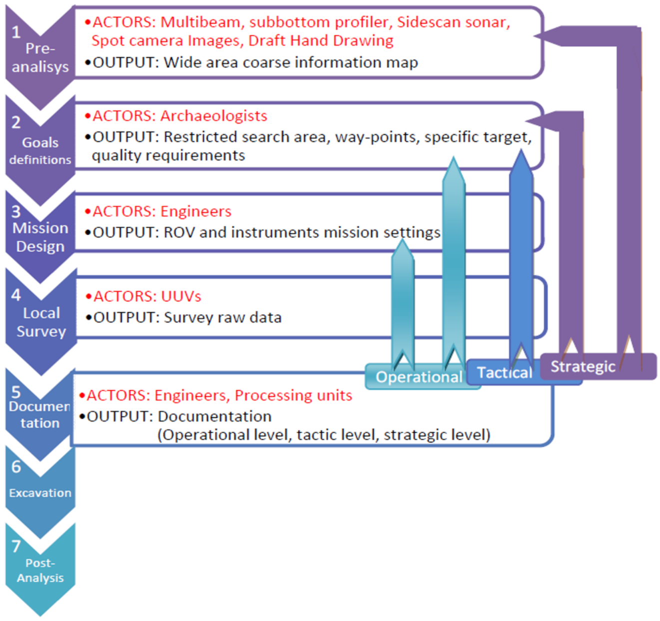


Figure 1. Activities in marine archaeological surveys

The pre-analysis is meant for the specification of the search area. Generally, information about archaeological remains is as vague about the objects to be identified as about their localization, so that a broad area must be covered in this initial phase. In many situations, this is done employing acoustic devices of various kinds (multibeam and sidescan sonar) for scanning the sea bottom. The output of this activity is a *preliminary map* of the area, whose scale is large or very large in comparison to the objects of (possible) interest, which appear as anomalies. From the analysis of the preliminary map, archaeologists define, in phase 2, a more restricted search area and design the mission by specifying its goals, defining a set of *qualitative indices of performance* and identifying *waypoints* and *targets* that deserve special attention. In rough terms, *qualitative indices of performance* measure the capacity to assess presence, kind and status of specific objects that archaeologist expect to locate during the survey.

The following phase 3 is devoted to plan and to design the survey mission, keeping into account the above information and the equipment's features (ROV/AUV manoeuvrability, payload capability, support vessel/boat characteristics and so on) as well as possible environmental constraints (depth, visibility, presence of current, tides and so on). In this phase, in particular, different solutions for structuring the area of interest are considered.

Then, local survey takes place in phase 4, according to the data gathering modalities and to the navigation specifications defined in the previous phase and documentation of the site, phase 5, follows next. Part of the data is processed on-line, that is during the acquisition, in order to produce 2D photographic maps of the explored area. It is in this phase that the information needed for closing the loop is generated. The control loop closes both at the *goal definition* level and at the *mission design* level. Feedback at the *goal definition* level represents a relevant novelty in the way of governing the data acquisition process in the underwater archaeological practice. Feedback action is generated checking qualitative indices of performances on the basis of archaeological evidence and, in case, it modifies objectives as well as the waypoints and targets. Feedback at the *mission design* level is more standard from the control theoretic point of view, but here it is important to point out that visual inspection of the available information (namely, of the 2D photographic maps) allows to assure the desired coverage of the area in terms of spatial density and of quality of the images, compensating for possible performance limitations of the guidance and positioning system of the ROV. This gives the possibility to employ efficiently also low-cost technologies, avoiding the necessity of collecting redundant data for guaranteeing coverage, with an obvious reduction of costs. Finally, a documentation of the marine site is produced from the post analysis of the data gathered during the (various) surveys. The analysis may reveal some deficiency in the data and a consequential need for the re-execution of some of the previous activities.

Experiments aimed at revising the traditional technique and at developing a new, partially automated procedure were performed at three different underwater sites: near the Island of Pianosa, Italy, in October 2006; near the Island of San Nicola, Italy, in spring 2007; in front of Sesimbra, Portugal, in October 2007. The three sites have very different characteristics and they offered the possibility to test several aspects of the data gathering procedure, using different equipment and letting the methodology to evolve in order to cope with increasing difficulties (see also [10], [22]).

Large scale maps (*preliminary maps*) produced in the preliminary broad search may differ greatly on each mission. In particular, in Pianosa, a geo-referenced sonar map was obtained by merging multi-beam sonar data taken from a surface vessel with DGPS information. The reduced depth of the site (about 30m) made possible to obtain a sufficiently detailed maps, where archaeological remains are identified by anomalies in the acoustic response, from the surface. At San Nicola, due to budgetary constraints and to the considerable depth (about 60 m), only a rough map without precise geographical references, produced by merging data collected in a series of independent and uncorrelated dives, was available. Essentially, the information reduced to the indication of some points of interest on a nautical map. Finally, in Sesimbra, the situation was very similar to the one experienced in San Nicola. Due to depth, acoustic maps constructed from the surface were not sufficiently detailed to be useful and technical problems caused geo-referencing to be scarcely reliable. Also in this case, only the indication of some points of interest on a nautical map was available.

Different configurations of the ROV and of the data gathering system were experienced in the three missions. In Pianosa, the ROV was equipped with a CCD video camera, a high quality still camera (Nikon DH2 with 14 mm Sigma lens) and two flashes (Nikon SB800). Both video and high resolution still images were captured. In San Nicola, the still camera was not mounted onboard, but the video camera was substituted by a new FullHD digital video camera of better quality. Only video frames were therefore available for documenting the site, but, in spite of the limitation due to their (comparatively) low resolution, this was enough for obtaining valuable information about the characteristics of the site. Both the still camera and the digital video camera were available in Sesimbra and collected data were of the same kind of those obtained during the mission at Pianosa. Practical procedure for data gathering, did not differ greatly in all the three missions. During each launch, the ROV executed a number of transects at the speed of about 1kn, at an average distance from the sea bottom of about 3m. Possible depth corrections could take place accounting for sea bed morphology, so to acquire images from a constant distance from the subject. In those conditions, each video frame covers an area of about 3m x 3m and video stream provides a complete coverage of a 3m wide corridor when the ROV moves along a linear path, assuring an overlap of about 60% between consecutive frames. The video camera takes 25 frames per second and, in order to have a complete documentation, the video stream was recorded by a VCR. The video stream was sampled at a frequency of 5 Hz (getting one frame over 5) by the NGC system of the ROV (implemented on a PXI/PC station) and sampled images were digitally recorded. Pictures taken by the photo camera, when present, covered more or less the same area framed by the video camera (average difference was about 5%) and were recorded on the camera own flash memory.

Geo-referencing, in Pianosa, was obtained by acquiring the position of the ROV with respect to the supply vessel by means of an USBL (Sonardyne Scout USBL) and by relating this to the DGPS position of the vessel. By keeping the ROV in stationary position on artificial landmarks for few minutes, repeated measurements of their position were taken and, filtering these, the geographic coordinates of the landmarks were computed. At San Nicola and at Sesimbra, for different reasons, only GPS data (not DGPS) were available for geo-referencing. The position of one transponder deployed on the sea bottom, in those cases, was evaluated filtering series of measurements. In every mission, acoustic images of the sea bottom, in addition to optical ones, were acquired by means of the on-board scanning sonar and registered by the NGC system of the ROV at a frequency of 10 Hz.

3. DATA PROCESSING

In the proposed procedural architecture, data processing takes place at three levels, which differ on time requirements and algorithm complexity, so to close different control loops at each phase of the survey activity. Controlling the process in closed loop fashion helps in speeding it up and in improving the overall efficiency. The different processing levels are called *operative level*, *tactical level* and *strategic level*, respectively, and they refer to a *short-term* decision horizon, a *medium-term* one and at *long-term* one, respectively (see Figure 2). Processing at the *operative level* is performed *on-line*, so to produce promptly a draft representation of the site and of the finds therein, greatly enhancing the spatial perception of the environment. Processing at the other two levels takes place *off-line*: at the *tactical level*, typically, it is performed daily, at the end of each survey by implementing accurate algorithms, which further elaborate the previously recorded data. Finally, processing at the third, *strategic level* takes place only at the completion of the whole mission and it considers the entire data set gathered in the various daily surveys. Structuring the whole process around a number of inner feedback loops as illustrated in Figure 1 is the key, innovative feature of the proposed methodology and the one which practically compensates for equipment limitations.

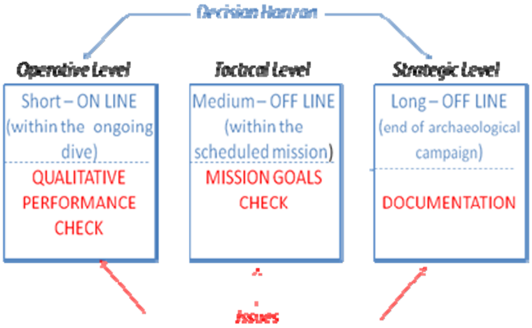


Figure 2. Three-level data processing.

The motivations for performing a first data processing at the operative level originate from the need to inform promptly operators and archaeologists who conduct the survey on the actual outcome of the process, so that corrective actions can be possibly triggered on line, during the current operation. While the ROV proceeds, sensor data are displayed on a M/M interface in diverse forms: video images, maps and "augmented" images and "augmented" maps (JPEG/EXIF images files, GIS layers). The video stream captured by the video camera can be observed directly on a screen, allowing to monitor the survey process and to detect possible unexpected objects or potentially faulty or dangerous situations. From the video stream, the operators can construct in their mind virtual representations of the explored environment, but this requires constant concentration and good perception of the ROV's displacements and it results very difficult for archaeologists which are not specifically trained. Moreover, individual representations are highly subjective and, not being shareable, they cannot provide concrete evidence for taking corrective actions. To improve this situation, the idea is to use sensory data, i.e. sampled optical digital frames from the video stream and acoustic images from the sonar unit, together with navigation data, to create dynamically simple maps of the site that are made available on-line to the operators and to the archaeologists. Such maps, although in a simple form in order to cope with the time and complexity constraints, provide an objective representation of the environment and they give precise information on the survey process.

The whole process starts by organizing the data into a set of files in JPEG/EXIF format as follows. Every picture sampled from the video stream (relatively low quality picture) is associated with additional data which may include:

- x, y, z terrestrial coordinates of the ROV, from the (D)GPS-USBL positioning system,
- depth, from the depth meter;
- altitude from the sea bed, computed from sonar returns;
- heading, from the compass;
- pitch and roll angles, from the IMU;
- three axis linear accelerations and angular velocities from the IMU;
- thrusters' RPM, from the NGC system of the ROV;
- sonar images.

Basically, the association is performed according to the time of acquisition, indicated by a timestamp, and consistency is assured by synchronizing all the systems on board the vehicle, including the video and still cameras, and the USBL system with GPS time at the beginning of the survey. Differences in the acquisition rates of each sensor need to be accounted for and this require operations which may include averaging, interpolation or filtering, according to the update rate and other characteristics of the sensor and of the produced signal. Each JPEG/EXIF file obtained contains an image in the JPEG area and it records, in particular, the information about the camera position, orientation and distance from the subject at approximately the shooting time in the EXIF area. Approximation depends on the sensory system characteristics, the specific procedures chosen for associating data, delays in data transmission. In particular, the position data coming from the USBL positioning system is the result of a Kalman filtering process that produces about one measurement each second with a computable delay d (given by $d=m/v$, where $m=(x^2+y^2+z^2)^{1/2}$ is the slant range and v is the sound's speed in water). Position data are associated to each sampled image, taking into account the delay and the timestamp. In the average, 5 images, sampled at each second, have associated the same position data, with an error that sums that due to the ROV displacement at 0.6kn (less than 30cm) and that due to the positioning systems (less 2% of the slant range). Navigation sensor data are sampled at 30 Hz and, as already said, sonar returns are acquired at 10Hz. Attitude data and depth measurements are averaged over a short period around each photo's timestamp and the result of the averaging is used for the data association.

At the operative level, the construction of the map takes place applying a Scale Invariant Feature Transform (SIFT) procedure [14] to the temporal sequence of sampled images, performing pair wise keypoint detection on each couple of subsequently acquired images. In order to speed up the processing, images are converted to grey scale images, discarding information about saturation and hue; data contained in the EXIF area (precisely: attitude and distance from the sea bottom) are used to orient uniformly and to scale the image contained in the JPEG area. The choice to apply a SIFT operator is motivated by the fact that, since the SIFT detector is invariant to image translation, scaling, and rotation and partially invariant to illumination changes and affine on 3D projection, it is well suited to underwater images' feature extraction. Photomosaic has already been widely used in underwater exploration and alternative techniques are available (see [13], [15], [18], [19]). By comparing SIFT output keypoints of two subsequent images I_k and I_{k-1} it is then possible to generate a photographic 2D mosaic map. In short, once n common keypoints are found, the SIFT algorithm search for the space-transformation matrix T that minimizes the distances between the image points p_{ik} ,$p_{i(k-1)}$ of each couple of matched keypoints. Namely, the following optimization problem is formulated and solved:

$$p_{ik} = \begin{bmatrix} x_{ik} \\ y_{ik} \\ 1 \end{bmatrix} \in I_k \quad p_{i(k-1)} = \begin{bmatrix} x_{i(k-1)} \\ y_{i(k-1)} \\ 1 \end{bmatrix} \in I_{k-1}$$

$$\min_{i=1,\dots,n} (Tp_{ik} - p_{i(k-1)})$$

where T is a space transformation matrix and n is the number of keypoints. Subsequent images are then glued together, according to the computed transformation. In this way, a growing "snake" mosaic is created by adding a picture at a time and the resulting 2D map is displayed on line on a monitor, allowing visual inspection by archeologists and operators. The operators can therefore check on possible ROV guidance problems and area coverage, closing a feedback loop at the *mission design* level and generating, if needed, a corrective action on the basis of objective, sharable information. The on-line availability of the 2D mosaic map, in addition, allows the archaeologists to orient themselves easily and promptly, making possible to exploit their competence for closing a second feedback loop at the *goal definition* level. Achievement of the fixed *qualitative indices of performance* can be checked and, in case, (some of) the mission parameters (e.g. data density, shooting modalities, distance from the sea bed) can be modified. In addition, new evidence from the site, gained by means of the 2D mosaic map, may motivate modification in the choice of *waypoints* and *targets*. Since the photomosaicing process produces a realistic representation only if the seabed is almost flat, altitude and depth are monitored to check such assumption and, in case, to signal deviations that can drastically reduce the validity of the 2D map. The mosaicing process is schematically illustrated in Figure 3. The table in Figure 4 describes the characteristics of the process with respect to a sample series of images for each site. Each series consists of 10, sequentially acquired images of 728x480 pixels; keypoints # indicate the minimum and the maximum number of keypoints used to match pairs of sequential images in the series. The mean matching error is computed averaging the matching error for each pair of sequential images. Time

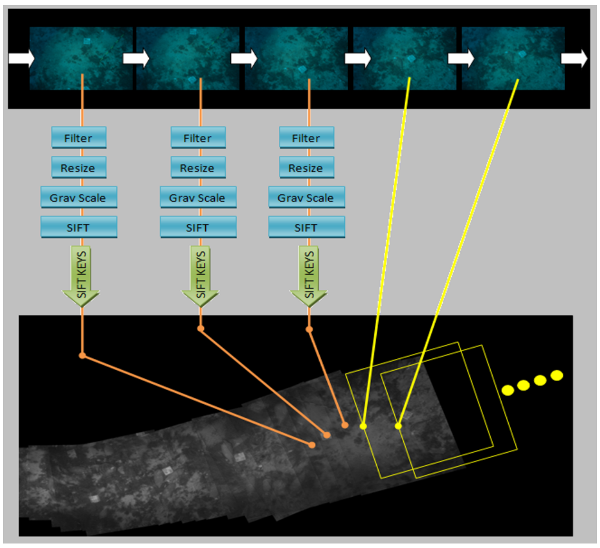


Figure 3. Scheme of the mosaicing process.

denotes the average time in seconds required to mach and to add a single images to the mosaic.

Position information included in the EXIF area are, at the same time, used to build up, with the 2D mosaic map, a layer of a GIS [12], which, on other different layers, incorporates information over a larger area, coming from a variety of sources (in particular, also from previous surveys). Also the GIS representation is made available on-line to the archaeologists that conduct the survey, helping them to locate the actual findings in a larger context and to interpret the local situation in wider scenarios, enhancing significantly their global situation awareness. The open source OpenMap package is employed to represent and manipulate geospatial information in order to construct the GIS layer. Practically, by means of a specific tool developed in the Matlab software environment, USBL/DGPS data are directly obtained from the positioning system through a RS232 port, processed on a PC and mapped onto a new layer on OpenMap using the XML Client protocol. Acquired data can in this way be merged with geographic maps of the area, like those that can be obtained, e.g., from the NASA world geographic archive. It is possible in this way to have a geographic representation of the path followed by the ROV during the survey, which is updated practically in real time.

At the tactical level, processing takes place off-line, allowing for more accurate photomosaic maps to be produced. High

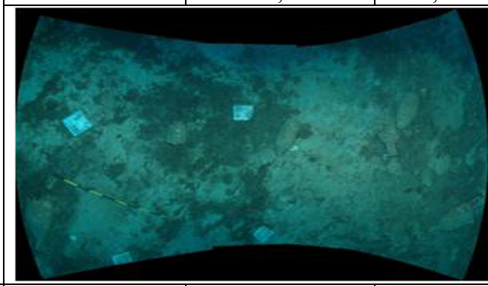
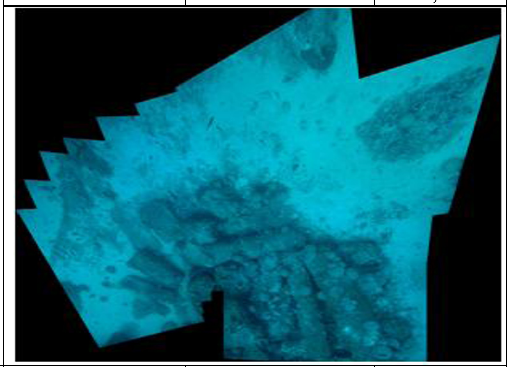
Site	Keypoints # (min-max)	Mean matching error (pixel)	Time (s)
Pianosa	184-217	2,5	0,45
			
Tremiti	60-231	3	1,30
			
Sesimbra	183-209	3	0,50
			

Figure 4. Characteristics of the mosaicing process.

quality images, normally stored in the camera own flash memory, are available at this stage and new JPEG/EXIF files can be constructed, using the timestamp for data association, by means of the same procedure illustrated above. In this way, two sets of correlated JPEG/EXIF files, respectively a large one with low quality images and a smaller one with high quality images are produced. Files in the new set are processed in order to construct new, more accurate local maps by mosaicing techniques, accounting for all overlapping information, including that coming from images that were not taken sequentially. To make this possible, position and attitude data contained in the EXIF area are used for establishing correlation between images, essentially identifying for each one of them those taken (not necessarily sequentially) from close positions and which presumably overlap, that is depict (part of) the same area of the sea bed. Although not performed on-line, processing at the tactical level takes a relatively short computational time and its product can be made available shortly after the whole set of data has been gathered. The decision horizon in this case can be fixed within one day and, at logical level, this allows the closure of a further feedback loop at the *goal definition* level (see Figure 1 and Figure 2).

Maps obtained from the processing at the tactical level form additional layers of the GIS, which can be further enriched by inclusion of 3D maps, derived from the mosaic maps with the aid of sonar data and photogrammetric techniques in a subsequent off-line processing at the strategic level. The decision horizon in this case corresponds to the entire archaeological campaign. Depending on data quality, this processing phase may take a relatively long computational time [8], [10]. Additional information can be added to generate augmented maps. In general, one can add information gathered on the site (concerning e.g. the structural characteristics of the sea bottom or those of specific objects revealed by their acoustic response, as well as the presence of buried objects detected by sub-bottom profilers) or extracted from databases and libraries (like e.g. information on the characteristics of recognized artifacts). Representing data gathered in various campaigns as GIS layers, evolution and possible degradation of the condition of the site can be monitored. The results of the final processing represent the documentation on the site available at the end of the archaeological campaign.

4. CONCLUSIONS

In order to facilitate the adoption of feasible and efficient robotics technologies in underwater archaeology, the data gathering process has been revised and redesigned. The main innovative characteristic is the use of fast, on-line construction of mosaic maps in governing the whole exploration process. Such methodology can be easily scaled and adapted to different situations, according to the available equipment and to financial and human resources. This makes it suitable for common practice in marine archaeology, in order to maximize results with respect to costs and risks. In the future, the objective is to consolidate the proposed methodology by exploiting more extensively autonomous devices and systems, in order to provide performing and more versatile data gathering tools for deep waters.

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