The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST
(2011), pp. 1–4
M. Dellepiane, F. Niccolucci, S. Pena Serna, H. Rushmeier, and L. Van Gool (Editors)

THESAURUS: Techniques for Underwater Exploration and Archeology through Swarms of Autonomous Vehicles

B. Allotta[2a], A. Caiti[3], M. Cocco[1,5], C. Colombo[2b], W. Daviddi, L. Gualdesi[3,5], D. La Monica[4], D. Moroni[1], G. Pieri[1], O. Salvetti[1], M. Tampucc

[1]Institute of Information Science and Technologies (ISTI),National Research Council of Italy (CNR), Pisa, Italy
[2a]Department of Energy Engineering "Sergio Stecco," University of Florence, Italy
[2b]Department of Systems and Informatics, University of Florence, Italy
[3]Research Center in Robotics and Bioengineering "E. Piaggio," University of Pisa, Italy
[4]Scuola Normale Superiore, Pisa, Italy
[5]EDGELAB S.R.L., Portoferraio, Italy

Abstract

The THESAURUS project (2011-2013) is financed by Regione Toscana (Italy) in the framework of the "FAS" program 2007-2013 under Deliberation CIPE (Italian government) 166/2007. The overall goal of THESAURUS project is to develop multidisciplinary methodologies and technologies to detect, catalogue and document underwater artifacts and wreckage with archaeological and ethno-anthropological value. In particular, specially designed Autonomous Underwater Vehicles (AUVs) will be used to systematically explore the sea floor in a cooperative way, by collecting and analyzing in real time heterogeneous data from acoustic, optical and magnetic sensors with the aim of promptly detecting objects of interest. Data recorded from AUVs missions will also be analyzed and integrated off-line, by building large-scale sea-floor maps and 3D reconstructions for granting virtual access to underwater sites.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Depth cues, Motion, Object recognition H.2.8 [Information Systems]: Database Applications—Image databases

1. Introduction and Project overview

In the last years, there has been an increasing interest in the exploration of possibly large underwater areas, in connection with scientific surveys ranging from geology (study of hydrothermal vents) to biology (study of benthic ecosystems), from forensics science (airplane accidents) to archeology (ancient shipwrecks and settlements). In such missions, the use of robotic vehicles or towed sleds is essential to automatically acquire different kind of data from the seafloor. In this context, recent research, and technology transfer projects oriented to archeology ([DSC*08], [NC09] as well as the European projects VENUS and ARCHEOMED), have focused their attention on the development of low cost technologies for the survey process automation, documentation and systematic monitoring of wrecks in *known* sites. However, from a scientific point of view, all the issues related to sustainable (e.g., low-cost), systematic and large-scale exploration for the search of *new* sites still remain to be addressed. Due to the sufficient maturity in the technological sector of underwater robotics, computer vision and photogrammetry, a research project named THESAURUS has been prepared to address these issues. To complete the framework, the project also addresses topics related to i) data storing, ii) data representation, and iii) retrieval, making this issue strictly linked to the exploration. In particular, data, obtained from systematic surveys carried out by autonomous robots, may provide to the archaeologist a set of information substantially different from the traditional documentation and, therefore, they need a proper systematization.

THESAURUS has been submitted and financed in the framework of the "FAS" program 2007-2013 of the Regione Toscana (Italy). Project activities started on March 2011 and are foreseen to run until 2013. Motivated by the aforementioned considerations, the overall goal of THESAURUS project is to develop multidisciplinary methodologies and technologies to detect, catalogue and document underwater

artifacts and wreckage with archaeological and ethnoanthropological value. In particular, THESAURUS aims at:

- Investigating and experimentally evaluating the use of swarms of Autonomus Underwater Vehcicles (AUVs) for the systematic research and mapping of sea floors with archeological interest by means of optical, acoustic and magnetic sensors;
- Studying methods for the visualization and 3D rendering of the sites explored by the AUV swarm and for the integration of other information, including historic-archeological findings;
- Defining an integrated repository allowing for the extraction and retrieval of baseline data for planning AUV missions, of specialist historic and archaeological information and of general public information for granting virtual access to underwater sites.

In agreement with the "Sopraintendenza per I Beni Archeologici della Toscana", THESAURUS will accomplish testing activities in the Tuscany Archipelago. In particular, several known and new underwater sites will be explored and catalogued. In addition, by exploiting the results of historical research activities, explorations will be conducted along ancients routes and around shipwreck places. The aim of this paper is to present the key and most challenging points of THESAURUS, In particular, with respect to [ACC*11] where emphasis was given to robotics, in this paper the focus is given to aspects related to computer vision, virtual reality and information technology issues.

2. Underwater robotics

In THESAURUS, a new class of vehicles (jokingly named in Italian "Tifone", after the famous movie "The Hunt for Red October") is being designed and developed. Figure 1 shows the design of the current prototype. The Tifone AUV family will be capable of 300m depth and will be equipped with techniques for autonomous navigation. Various sensors and navigation systems will be available for Tifone AUVs; in particular the equipment will be modular, thus allowing to tailor the sensor payload to the planned mission.

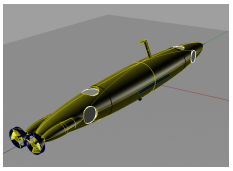

Figure 1: *Design of the Tifone AUV.*

In THESAURUS, Tifone AUVs will be deployed in a swarm. To this end, algorithms for optimal search, cooperation and coordination of vehicles, adaptive sampling for full coverage of large areas of sea floor will be incorporated. Members of the swarm will not be identical, but a certain degree of specialization will be included and exploited for improved performance. For example, each member will be equipped with low-cost sensors such as Inertial Measurement Unit (IMU), magnetometer and depth sensors. Instead, high accuracy velocity sensor such as the Doppler Velocity Log (DVL) will be installed only on some members of the swarm. Since acoustic modems, used for communication among the swarm, can provide the time of flight from an AUV to another one, the position estimated with a range-based algorithm may be fused with the one estimated by DVL. Thus, even without having a DVL on each vehicle, the positions of the member of the swarm may be estimated accurately, avoiding unbounded error growth during the navigation. The specialization of the sensors installed on board for sea-floor data acquisition brings clearly several advantages in a collaborative environment among the member of the swarm. Moreover, each of the vehicles will be equipped with optical, magnetic or acoustic sensors and will be capable to perform an accurate scanning for some of these modalities. If a signature of human artifacts is detected by one of these modalities (using the methods described in Section 3.1) in some point by a vehicle, then the mission may be re-planned on line at a *swarm level*, i.e., the other members of the swarm may be required to explore around the same point making use of the most suitable sensing technology.

3. Image analysis and understanding

Another crucial and innovative issue in THESAURUS is the development of an automatic system for image and map analysis and recognition. The sea-floor exploration, through the sensors on the AUV platform, will produce a large amount of data (optical images, magnetic anomalies and sonograms). Proper software modules will be developed for the classification, analysis and storage of these data using automatic pattern recognition methods. In particular, data processing and interpretation will be performed at two levels: i) directly *on board* the underwater vehicles (under distributed and real-time condition), and ii) in post-processing for accurate analysis, classification and storage of the acquired data.

3.1. Real time image analysis for the automatic detection of region of interests

Regarding the first level, data acquired from sensors hosted on the AUV will be directly elaborated on-board. Elaboration will use real-time algorithms specifically designed to run on embedded systems. In order to identify scenes of interest and report them to the other members of the swarm, the AUVs will be equipped with intelligent methods for the real-time interpretation of acquired information. Then, the vehicles, in a co-operative way, will perform more specific and thorough investigation in the indicated area. In particular, the on-board system of the individual vehicle will use the information provided by sensors (optical, acoustic, mag-

netic) to evaluate the probability that in a certain area there are signatures of human artifacts.

The integration of high-level visual information directly on-board has a strong innovative feature, both from a scientific and applicative point of view. In particular, the introduction of visual information allows the design of multimodal systems, e.g., based on information obtained from different sources (scalar sensors, low-resolution and high-resolution images, sonograms), with a gain in terms of adaptability of the swarm, according to the specifications of the exploration in progress. From the scientific point of view, it appears innovative to design and develop algorithms for the exploration based on a co-operative swarm, driven by a real time interpretation of the acquired data.

For example, for what regards optical images, texture descriptors (see e.g. [RH99]) will be taken into account since they allow to discriminate areas with chaotic background from areas that exhibit regularity and that, therefore, may be affected by the presence artifacts or wrecks. In addition, we will focus on methods for the identification of 2D features in the images, such as relevant portions of straight lines and conics, whose density in a given image is certainly an index of being in front of an artifact. The use of 3D features, such as planes and quadrics, will also be considered. Hence, an online 3D reconstruction of the sea-floor will be performed by using either acoustic data form side scan sonars or optical image sequences. In the first case shape from shading approach will be followed (e.g. [CPL07]), in the latter robust Structure From Motion (SFM) algorithms will be employed (e.g. [PVGV*04]), that will provide a simultaneous estimate both of structure and of the rigid vehicle motion. For avoiding too expensive computational burden, such online reconstruction will be performed at a frequency lower that the actual frame rate, whilst the full acquired data will be accurately processed off-line as described below.

3.2. Multiview analysis and 3D reconstruction of large scale maps

The real-time processing on-board the vehicles will be complemented with an arsenal of methods for accurate offline analysis of the data stream, covering the complete pipeline from raw data acquisition to image fusion, 3D reconstruction and semantic annotation. The obtained results will be conveyed in the THESAURUS information system (Section 4).

First, methods for the registration of two-dimensional images and for the creation of geo-referenced large scale maps of sea-floor will be designed and developed. Following the recent research trends [PES09], an SFM strategy encompassing bundle adjustment will be investigated for allowing the creation of accurate maps of the sea-floor and extracting 3D structure. Then, methods for the automatic interpretation of the observed scenes will be designed, also considering 3D clues. For special classes of artifacts (to be determined according to the results of the historical and archival research that will be conducted in the Project), detectors will be trained for performing an automatic screening of the maps of interest. Besides well established methods (e.g [VJ04]), techniques for robust object detection, also in presence of partial occlusion and based on object subparts, will also be considered (e.g. [FGMR10]). Thus, the introduction of such refinements is essential to obtain adequate performance of the algorithms within the underwater environment and to make possible the identification of fragments and objects only partially protruding from the sea-floor. In addition, for particular classes of objects for which 3D models are available, object recognition through fitting of 3D models will be performed. For example, in a portion of the scene in which a quadric has been already identified, fitting of different amphora models may be attempted, using for example algorithms like iterative closest point. This will result in a view-independent recognition of artifacts of potential archaeological interest that may be effective also in case of strong occlusions. This is a modern and promising approach, successfully applied in face recognition [HV08], but not yet explored in underwater scenarios. Finally, robustness with respect to 3D noise (due for example to seaweeds, shells and other concretions) will also be considered by enhancing the current shape comparison techniques. For further refining the 3D reconstruction, the possibility to use a system for structured light projection (e.g., laser light generators for underwater applications) will also be considered. In particular, during the underwater exploration, in case an area deemed with high probability of artifacts is found, the AUVs will have the possibility to scan by laser line the sea-floor. Finally the 3D reconstruction of the sea-floor will permit building an interactive virtual environment of underwater archaeological sites through visual synthesis techniques. Realistic rendering will be made available through the acquisition of chromatic texture information associated to the structure of the scene. To this end, a virtual navigation system application will be developed which will allow to change the point of sight and other optical parameters (zoom, field of view,...) in an interactive way. Mixed reality applications will also be investigated for enriching the virtual visit experience by presenting other metadata of interest regarding the underwater site.

4. THESAURUS information system and smart data access

Project activities involve multidisciplinary fields, both technological and humanistic, such as underwater robotics, historical and archaeological research and its technological integration, artificial intelligence applied to the treatment of large amounts of data and oceanographic sensors. Thus, a key and challenging point in THESAURUS is the technological integration between these fields and the convergence of know-how. Therefore, the information system, developed within the project, has to guarantee and promote the col-

laboration among the technologists, computer scientist and historical and artistic partners. With the goal of reaching an interoperability and integration of the project results with major activities in these fields, and using similar technologies and standards, we are considering initiatives like Europeana and 3D-COFORM. The information system manages and integrates the large amount of heterogeneous data produced by the project activities, and provides advanced and smart functionalities for data storage and access. During the storage phase, due to the heterogeneous data formats, the information system has to exploit several data fusion techniques in order to organize data into a common structure. In particular, the system manages i) structured sequences (such as images, magnetic anomalies, sonograms and 3D models), ii) semi-structured sequences (such as geo-referenced data), and iii) not structured ones (such as raw data). The proper data fusion techniques and the architectural and structural requirements will be obtained as a result of activities focused i) on the definition of metadata standards, ii) on the semantic modeling of the domain, and iii) on the analysis of data types, formats and relations.

5. Expected results and conclusions

The data obtained from the historical and documental analysis and those obtained from the underwater campaign research will be made available to the scientific community through a web portal dedicated with secure control of accesses. A part of the information obtained and of the results of research and analysis carried out will be made available to the general public, while confidential data for the security of the site will be made available only through reserved access modalities. As in this context, there will be elaborated and distributed communication products for the enhancement of the information collected through the application of the implemented tools and technologies (reports of the sites, reports of the art-works, web portal, multimedia data, etc.). We will proceed to the dissemination of results through the realization of audio-visual material for study, dissemination and educational purposes. In the acquisition of knowledge it should be made known to the world of scholars and the general public all the assets identified and their historical events. At the beginning of this phase there will be availability of: i) Populated records related to underwater archaeological or historical sites, sunken ships of historical and/or archaeological interest, submerged loads of historical and/or archaeological interest, submerged artefacts of historical and/or archaeological interest, and ii) Reconstructed historical events based on data collected during the preliminary archive and bibliographic research. These products will allow to design, build and populate the database, where the above mentioned records will be available. Besides that, at this stage the aim is to construct various kinds of "cultural products" to be used in various ways, addressing different audiences, with the perspective to disseminate knowledge regarding the underwater cultural heritage and to increase the sensitivity to the problem of its preservation. These tools are very technical, useful and interesting for scholars, but less attractive for a wider public. The objective of this work should be also to make more attractive this information, by identifying new forms of dissemination. First of all integration should be performed of knowledge collected during the preliminary archival and bibliographic investigation or with new data extracted from the missions. Hopefully, reconstructed and documented cases will be further enriched by the data of the missions. Data integration will lead to the production of more complete and updated historical reconstructions based on new data and problems. The exploitation of results obtained in the project was held into particular consideration and a whole work package is dedicated exclusively to the dissemination of large-scale activities.

Acknowledgements

This work has been partially supported by PAR FAS Tuscany Project “THESAURUS” – Techniques for Underwater Exploration and Archeology through Swarms of Autonomous Vehicles.

References

[ACC*11] ALLOTTA B., CAITI A., COCCO M., COLOMBO C., DAVIDDI W., GUALDESI L., LA MONICA D., SALVETTI O.: Thesaurus: A marine robotics project for archaeological applications. In *15th International Conference on Advanced Robotics ICAR 2011* (Tallinn, Estonia, 2011). 2

[CPL07] COIRAS E., PETILLOT Y. R., LANE D. M.: Multiresolution 3-D reconstruction from side-scan sonar images. *IEEE Transactions on Image Processing 16* (2007), 382–390. 3

[DSC*08] DRAP P., SEINTURIER J., CONTE G., CAITI A., SCARADOZZI D., ZANOLI S., GAMBOGI P.: Underwater cartography for archaeology in the VENUS project. *Geomatica 62*, 5 (2008), 419–427. 1

[FGMR10] FELZENSZWALB P. F., GIRSHICK R. B., MCALLESTER D. A., RAMANAN D.: Object detection with discriminatively trained part-based models. *IEEE Trans. Pattern Anal. Mach. Intell. 32*, 9 (2010), 1627–1645. 3

[HV08] HAAR F. B. T., VELTKAMP R. C.: 3d face model fitting for recognition. In *ECCV (4)* (2008), Forsyth D. A., Torr P. H. S., Zisserman A., (Eds.), vol. 5305 of *Lecture Notes in Computer Science*, Springer, pp. 652–664. 3

[NC09] NIETO X., CAU M. (Eds.):. *Arqueologia Nautica Mediterranea* (Gerona, 2009), CASC. 1

[PES09] PIZARRO O., EUSTICE R., SINGH H.: Large area 3-D reconstructions from underwater optical surveys. *Oceanic Engineering, IEEE Journal of 34*, 2 (april 2009), 150 –169. 3

[PVGV*04] POLLEFEYS M., VAN GOOL L., VERGAUWEN M., VERBIEST F., CORNELIS K., TOPS J., KOCH R.: Visual modeling with a hand-held camera. *International Journal of Computer Vision 59* (2004), 207–232. 3

[RH99] RANDEN T., HUSOY J.: Filtering for texture classification: a comparative study. *Pattern Analysis and Machine Intelligence, IEEE Transactions on 21*, 4 (apr 1999), 291 –310. 3

[VJ04] VIOLA P. A., JONES M. J.: Robust real-time face detection. *International Journal of Computer Vision 57*, 2 (2004), 137–154. 3