Underwater Archaeology: Available Techniques and Open Problems in Fully Automated Search and Inspection

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Abstract. The exploitation of marine technological innovations in the field of underwater archaeology has been mainly associated in the past to the exploration phase, in a sort of "treasure-hunt" fashion. However, the combined progress in such diverse field as underwater acoustics, robotics, image processing, computer graphics and decision support systems have not yet been fully integrated towards the need of underwater archaeological research. The paper reviews two different technological developments, in the fields of underwater acoustic and robotics, respectively, that may be merged toward the final goal of fully automated detection and inspection of an archaeological site. In particular, acoustical imaging methodologies based on 3-D backscattering measurements for remote inspection of buried artifacts will be reviewed. Moreover, the paper will also introduce vision-based robot control methodologies for fine positioning and accurate site survey, as well as higher level planning and control strategies, to be implemented in autonomous or semi-autonomous underwater vehicle.
Keywords: Underwater archaeology; Remotely Operated Vehicles; Underwater Acoustics

1. Introduction

The application of ICT (Information and Communication Technology) to the activities and problems of underwater archaeology is relatively recent and it has mainly emphasized the possibility of making new discoveries. Recent succesfull accounts have shown that, through unmanned equipment, it is possible to explore depths far beyond those usually reached by archaeological diving, and that this can lead to important, if not fundamental, discoveries (Ballard et al. 2002). Though certainly of scientific relevance, and also valuable from the point of view of fund-raising, this "tresure hunt" approach may shadow another potential of ICT application to marine archaeology, namely the possibility of automating much of the field work required for the exploration of an underwater site, in order to greatly reduce the costs and the human life risk associated to this operation. Although in itself less spectacular, this application is the one that may eventually have the greatest impact on archaeological research. Experiences and field examples of this second kind of application have been reported (Grand Ribaud 2002, Mindell 2004, Vettori et al. 2004). However, in most of these works, the technology in use has originally been developed for puroposes different from those of underwater archaeology. Moreover, some of the equipment in use requires skilled engineers for its proper operation, and it has a cost still very significant, and such to prevent its use from most of the archaeological research groups operating in the field. Our own experience in field work together with archaeologists (Vettori et al. 2004, see also the companion paper by Gambogi et al. in these proceedings) has shown that archaeologists need cheap, affordable equipment, that can be operated by a non-expert with a minimum amount of training: a sort of "plug and play" system, specifically oriented toward archaeological needs. Some existing search and inspection system are now close to this goal (for the simplicity of use, if not for the cost): it is the case of multibeam echosounders (Basciano 2004) and, to some extent, of side-scan sonars (...). More difficult it is still the situation regarding two specific problems that, if solved, may lead to a considerable pay-off in terms of applicability in archaeological research. These problems are the collection of photogrammetric data with automatic equipment, and the non invasive imaging of buried artifacts.

Automatic collection of photogrammetric data can in principle be performed with Autonomous or Remotely Operated Vehicles (AUVs or ROVs), properly equipped with camera and positioning sensors. Autonomous navigation over an archaeological site maintaining the precision requirements for a photogrammetric survey, however, is not yet a solved problem, at least if one does not want to rely on very specific, expensive and difficult to calibrate equipment (as for instance, underwater acoustic navigation with Long Base Line systems). In this paper we report our experience on a visual feedback approach, in which an underwater robot is precisely positioned on the basis of the camera data. Such positioning approach has the advantage of being applicable to any robot

equipped with some basic navigation sensors (compass, depth meter) and a camera, it does not need any other external equipment or facility, and it is a natural component of a SLAM (Self-Localization and Mapping) approach to area mapping, similar to those already employed by robots or team of robots in the exploration of other hostile environments (Dissanayake et al. 2001).
The problem of detection and subsequent remote inspection of buried remnants is very relevant to archaeological research in order to decide whether and where to start an underwater excavation. Existing sub-bottom echosounders do not have the necessary resolution for archaeological work, while standard side-scan sonars or multibeam echosounders do not have the necessary penetration. Incidentally, the same concern on buried artifacts detection/inspection is shared by other user groups with different needs, as for instance mine-hunting research and environmental/waste management research. In this paper we report some recent results from the environmental field that may have a long-lasting impact on archaeological research as well. In particular, the results have been obtained as a part of the European Union funded research project SITAR (Caiti et al. 2004), devoted to the risk assessment of seabed dumping sites where most of the dumped material is buried in tha seabottom.
Although the two applications presented here are independent one from the other, it has to be clear that both are basic components of a future system able, in perspective, to complete the inspection and the collection of scientific archaeological data at a given site in a fully automated manner.
The paper is organized as follows: in the next section the visual feedback approach to the positioning of underwater robots is reported, with some filed data obtained by trial tests. In the third section results from the SITAR project are reported, in particular regarding the prototype of a new generation side-scan sonar based on the so called parametric effect, and on a 3-D acoustical imaging methodology. Finally some conclusions are given.

2. Automatic ROV Positioning Via Visual Feedback

The basic component of an underwater robotic systems able to fullfill several complex tasks in automatic mode is the Navigation, Guidance and Control (NGC) module. A fairly general block diagram for such a module is depicted in Figure 1. From the bottom of the block diagram, it can be seen that the data from the vehicle sensors are fed back to a set of different modules, each one having the task of processing the raw sensor data for a specific purpose (obstacle avoidance, position/speed determination, etc.). In the figure it has been purposely introduced a visual signal processor module, that elaborates the vehicle camera data, and that it is central to the visual positioning system described in the following. Additional modules can be introduced on a case by case basis, depending on the specific robot tasks and on the specific payload sensors available. The outputs from the various modules are given to the navigation module, where they are merged in order to determine where the vehicle is (both in

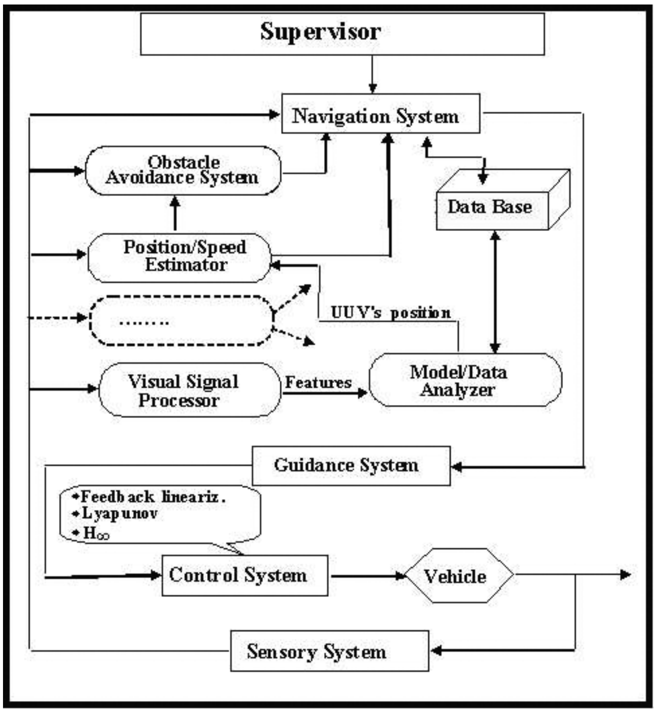

Fig. 1. Block diagram of the Navigation, Guidance and Control module of a generic autonomous underwater robot with visual feedback.

absolute and in relative positioning systems) with respect to where it should go (input from the supervisor module).
The discrepancy computed by the Navigation module between the current vehicle position and the scheduled one is given as input to the Guidance module, which in turns compute a command signal (where to go next, with what velocity and orientation) to be given to the Control module.The Control module computes the actuators signal (drives voltage input) of the vehicle in order to be close to the Guidance module command within a pre-specified accuracy, which can be task-dependent. The scheme is iterated at each new sampling from the vehicle sensors. It is important to emphasize that the conceptual scheme depicted is not dependent on the specific control law implemented, or on the specific sensor suite available to the vehicle. These (sometime critical) implementation decisions are embedded in the various modules of the block diagram. It is also worth noting that the supervisor module can either be a pre-programmed, very high level, module, or a human operator, building even fairly complex robot behaviours by specifying a sequence of basic robot tasks.
In Figure 1, the Visual Signal Processor block has been expanded indicating also the presence of a Model/Data Analyzer that compares the feature extracted from the Visual Processor with those present in the system Data Base. This functionality is at the core of the visual feedback positioning now described.
Essentially, the task is that of positioning the vehicle so that a given object recorded in the camera image is positioned at the center of the image. When the object is resting on the seabed, the operation is done at constant vehicle altitude over the seabed (or equivalently, assuming a flat seabed, at constant water depth). In addition to the camera image, a depth meter

and a compass are used as part of the sensory system for this task. The assumption of object resting on the seabed suits well archaeological applications, however the proposed scheme does not rely on this assumption, as illustrated in (Conte et al. 2004), where the same approach is described in more general terms, with additional experimental data with objects both on the seabed and in the water column.

The image processing part takes place in 3 successive steps. The first is the acquisition of a grey level image (Figure 2). It is assumed that at this stage the supervisor has already driven the robot in a position such that at least one object of interest is present in the image. In the second step the image is filtered and contours are extracted (Figure 3). Filtering consists essentially in grey level equalization in order to reduce the effect of different lighting conditions, while contour extraction is performed through Canny edge detection algorithm in order to select candidate contour points and then by application of a segmentation algorithm that groups candidate contour points in connected sets. Finally, in the third step the extracted contours are compared to a set of pre-defined geometrical shapes by means of Hough Transform. The contours consistent with those of the geometrical shapes presented in the system Data-Base, within the appropriate dimension range, are associate with the appropriate geometrical shape. In Figure 4 it is shown the output of this processing step, in which the amphora-like object of Figure 2 is finally associated to an elliptical shape. In the case in which in the same image more than one object associated to the data base geometrical shapes are present, the supervisor decides with respect to which of the extracted objects the positioning of the vehicle is going to be made.

The image of Figures 2–4 has been acquired by a CCD camera installed on the DIIGA Phantom S2 ROV. The vehicle is also equipped with a fluxgate compass, with 0.1 deg accuracy, and with a pressure gauge depth sensor, with 1 m accuracy. The ROV is also equipped with an Inertial Motion Unit (IMU), which, however, was not yet employed in the control scheme when the experimentation reported here was performed. The vehicle is actuated by 4 thrusters, and it enjoys 4 degrees of freedom: surge, heave, yaw and sway. The vehicle is passively stable in pitch and roll. The data from the vehicle sensor are transmitted to a PC station through the vehicle umbilical cable. The PC station, developed at the Polytechnical University in Ancona, performs the NGC processing, and then transmits the actuators control signal to the vehicle again through the umbilical cable. The supervisory module is presently performed by a human operator. The experimental results reported here, for both the image processing and the control algorithms, have been obtained in controlled conditions in a pool.

After determinaton of the geometrical shape, the processing target now becomes that of positioning the vehicle so that the shape is centered in the camera image. In the case of the ellipses, for instance, the center is taken as the intersection point, in pixels coordinates, of the two axes. This control action is performed directly in the camera coordinate system, i.e., with respect to the image pixels. The control problem is decoupled in the sequence of two independent control problems, one for the vertical position and one for the horizontal. The two control problems are tackled in sequence. For each motion in the camera image (horizontal, vertical), the available sensor signals are those from the compass (heading), depth meter and the processed camera image, sampled at 1 Hz rate. Simple PI control laws have been implemented for the two control problems, guaranteeing practical asymptotic stability of the system.

Experimental results confirm the theoretical expectations, as shown in Figure 5, where it can be seen that the horizontal positioning goal is indeed reached with exponential convergence toward zero of the error in the camera-based coordinate system. In the same figure it is also shown the command signal in terms of the angular velocity as generated from the guidance module. It can be seen that the control reference signal has also a rather smooth behaviour, ensuring that the ROV motion maintains indeed the object within the camera during the positioning task.

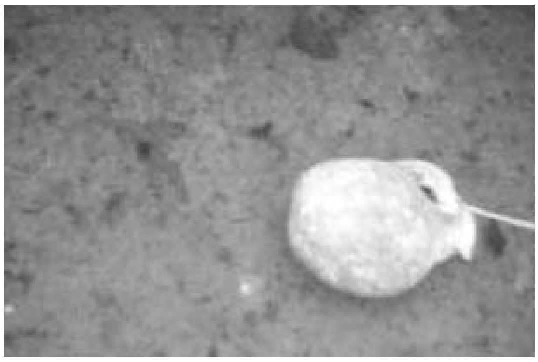

Fig. 2. Original image from the Phantom S2 vehicle camera, including an amphora-like object. Pool test.

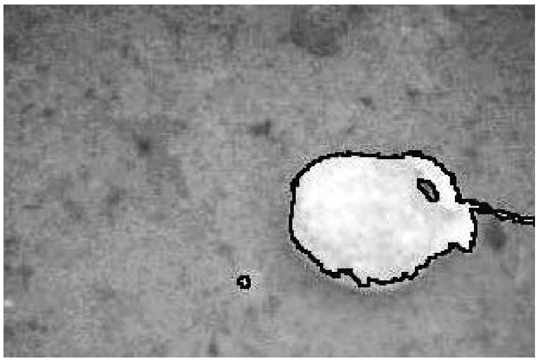

Fig. 3. Image filtering and contour extraction from the image of figure 2. Contour extraction line emphasized to enhance figure reading.

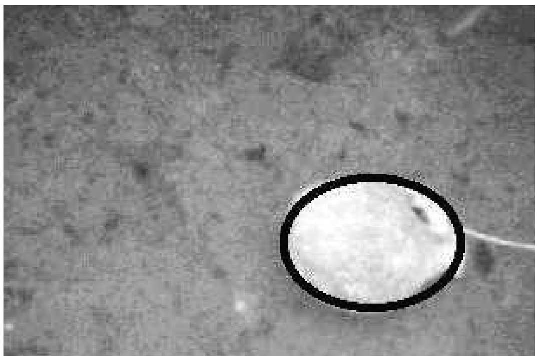

Fig. 4. Matching of the contour of Figure 3 with a predefined geometrical shape (ellipses) in the system data-base.

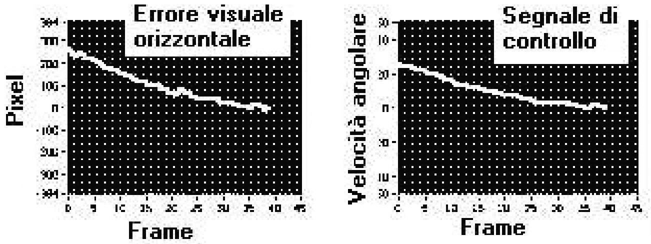

Fig. 5. Left: error in the horizontal position of the object with respect to the center of the image, as a function of the frame number (frame sampling: 1 Hz); Right: control reference (angular velocity) during motion.

3. Acoustic Detection of Buried Objects

In this section a different development is described, aiming at the design of an instrument able to survey portion of seabed and to detect possible buried artifacts at a depth and resolution compatible with archaeological needs. In particular, results from the development of a prototypal parametric side-scan aonar instrument are reported. The instrument development is part of the SITAR project (Caiti et al 2004), that has as overall goal that of providing instrumentation and methods for overall assessment of risk of seafloor dumpsites, when most of the dumped material is buried in the bottom. Along this line, one of the SITAR activities is that of devising acoustic methods for detection and inspection of containers buried at a maximum depth of 1 m, and with minimal dimensions equivalent to that of a cylinder of 1 m length and 0.1 m diameter. Such specification seems compatible with those required by archaeological search.

One of the instrumentation developed within SITAR is a side-scan sonar that, contrary to the standard instrumentation, exploits the so-called parametric effect, a consequence of nonlinear acoustic propagation in water: if an acoustic source transmits high energy acoustic signals in water at two different frequencies f1 and f2 , the dependence of the sound speed on the signal pressure level causes the generation of harmonic and sub-harmonic signals, in particular the generation of the so-called difference frequency $f0 = f2 – f1$. The advantage in this situation is that, with a high frequency source, it is possible to generate a low frequency signal with the same beam-pattern of the high frequency signals (i.e., a very narrow beam with negligible sidelobes), and with a transducer of reduced dimension (high frequency generation can be obtained with transducers whose size is smalle to that of low frequency generators). The advantage of a sub-bottom profiler built on the parametric effect principle for shallow geophyical investigations has been discussed in (Caiti et al. 1999). Within SITAR, the same effect is exploited in a side-scan sonar configuration; the traditional side-scan sonar configuration is depicted in Figure 6: the instrument, towed or installed on the ship hull, is composed by an array of co-located transmitters and receivers, and directed in order to acoustically illuminate a region of the seabed in the direction transverse to that of ship motion (the instrument "footprint"). In the SITAR-developed protorype, the acoustic transmitters have been designed in order to generate the parametric effect:

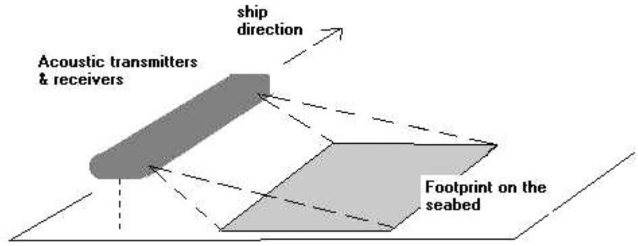

Fig. 6. Geometrical configuration of a side-scan sonar instrument.

with an array of parametric transducers, the instrument is able to record co-located acoustic images both at high and low frequency, with the beam pattern of the high frequency components. By comparing the high and low frequency images, it is thus possible to detect buried anomalies that can be associated to buried artifacts. The transmitting frequencies in the developed prototype has been selected in order to fullfill the size requirements on the objects to be detected. The system has been tested in a field trial in the Baltic Sea, Stockholm Archipelago, in the Autumn 2003, over a dismissed munition dump site. An example of the data gathered by the instrument is reported in Figure 7.

The most striking effect of Figure 7 is that of the bright spot visible only in the low frequency image, an indication that the acoustic reflection is coming from an object buried within the sub-bottom. Additional data and examples from the same field trial have been reported b (Zakharia et al. 2004).

The use of the parametric side-scan sonar in itself allows to detect a buried object, but not to inspect it, in order to decide, for instance, if it is a man-made object or a natural geological feature (e.g., a rock). Within SITAR, additional tasks are devoted to the development of the Multiple Aspect Scattering technique: this is essentially a repeated application of bi-static

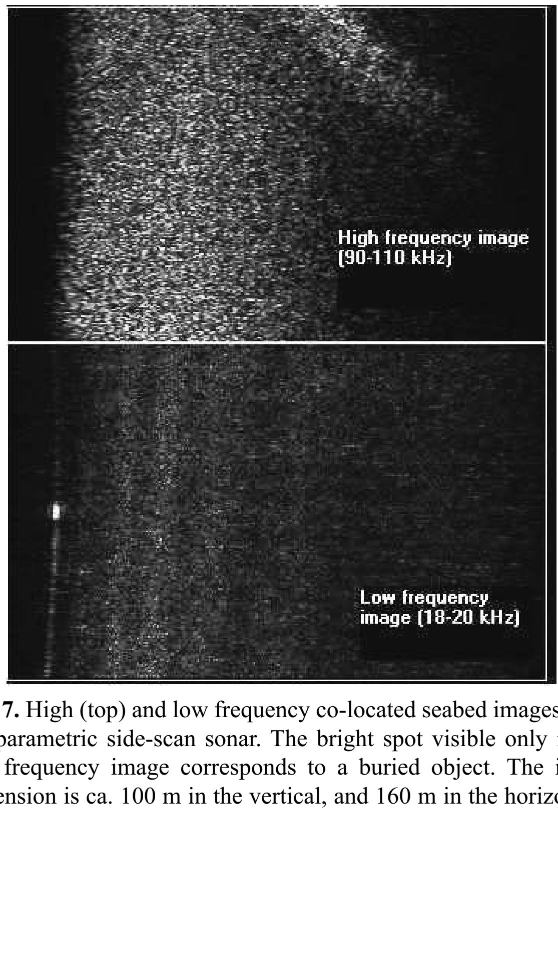

Fig. 7. High (top) and low frequency co-located seabed images from the parametric side-scan sonar. The bright spot visible only in the low frequency image corresponds to a buried object. The image dimension is ca. 100 m in the vertical, and 160 m in the horizontal.

scattering measurements at varying azimuthal and elevation angles, in order to recover the full 3-D acoustic scattered field. Assume a geometry as in Figure 8, which can be obtained by a sequence of bistatic configuration. Acoustic impulses are sent from the transmitter, and the scattered returns from the seabed and from the target are recorded at the various receiving positions. The received data are deconvolved, in order to associate each arrival to a given point in space (the scatterer), exploiting the knowledge of the source-receiver geometrical configuration (Dobbins et al. 2004). At each volume element ("voxel") is then possible to associate a scattering strength or a relative scattering intensity. Through this procedure a 3-D acoustic image can be composed.
In Figure 9 slices of the resulting volumetric image from a tyre-like buried object are shown. The volume image can then be given to a segmentation and feature extraction algorithms for final classification (Palmese et al., 2004).

4. Conclusions

Two distinct techniques have been presented, one for visual-based robot positioning and the other for acoustic detection and inspection of buried objects. Both techniques concur in the development of methodologies and equipment for fully automated search and inspection of an underwater archaeological site.

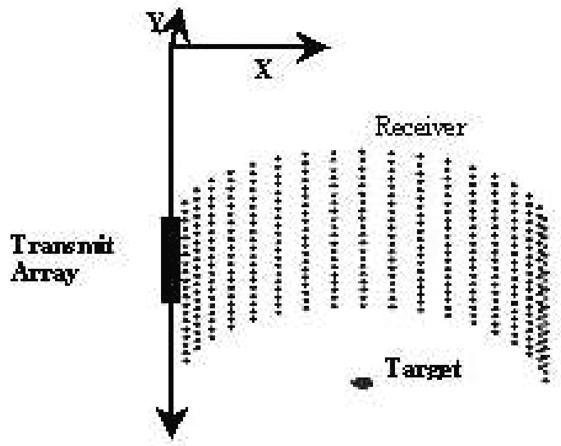

Fig. 8. Geometrical configuration for the Multiple Aspect Scattering Measurement technique. The configuration has been implemented by having the transmitting array installed on an ROV and rotating arounf the target position, and with a vertical fixed receiving array. Knowledge of the target position (a pre-requisite of the method) is available from parametric side-scan sonar data.

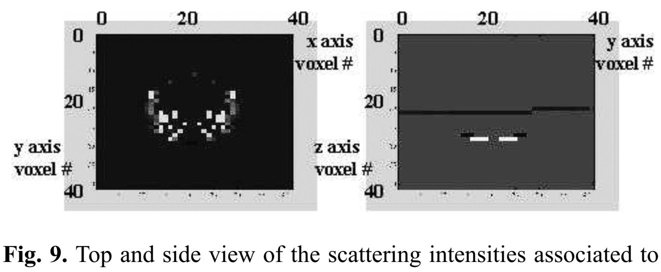

Fig. 9. Top and side view of the scattering intensities associated to the coordinates of the acoustically illuminated area. The data refers to a tyre-shaped object buried 40 cm in the sediment.

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