DATA GATHERING IN UNDERWATER ARCHAEOLOGY BY MEANS OF A REMOTELY OPERATED VEHICLE

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ABSTRACT:

This work describes the procedures and methodology employed in recent mission at sea for gathering data from submerged sites of archaeological interest. The emphasis in this activity is mainly in developing, testing and validating solutions that simplify the work of archaeologist by employing unmanned robotic vehicles and automatic procedures and that can be applied to deep water sites that are not reachable by divers.

1. INTRODUCTION

One of the activities planned in the framework of the European Research Project VENUS (see, for more information on the project, the website www.venus-project.eu and (Drap, 2006)) concerns the development of procedures and best practices for the use of unmanned underwater vehicle (UUV) in data gathering from submerged sites of archaeological interest.

Experiences of various kind and field examples in this area have already been reported in the literature (Ballard, 2002; Gambogi, 2004; Mindell, 2004; Vettori, 2004).

In this paper, we will describe the experience carried on by the team of the Italian Interuniversity Centre for Integrated Systems for the Marine Environment (ISME) during a two-week mission on a site located in the proximity of Pianosa Island, in the Tyrrhenian Sea. During the mission, the team has operated a small-class Remotely Operated Vehicle (ROV) DOE Phantom S2, equipped with sonar and cameras for collecting acoustic and optical images of a sea-bottom area of about 50m^2, at a depth of 35 m. The main problems to deal with, in this phase of the research project, concern the navigation and guidance of the ROV (Conte, 2004) and the association, integration and fusion of data gathered by heterogeneous sensors. By structuring the data into a coherent set, the primary objective is to obtain adequate, sufficient information for constructing an augmented, three dimensional map of the explored site. Previous work in the same line has been reported in (Caiti, 2004; Caiti, 2006)

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The underwater site of interest has been first surveyed by means of a side scan sonar and scanned data have been used to construct a preliminary, large scale map with bathymetric information that we will call *physical map*. By means of DGPS measurements, the map has been endowed with a geographic coordinate system corresponding to the terrestrial one. During ROV operations, the vehicle position has been monitored in real time by a USBL/DGPS system. In particular, acoustic measurements have been used to locate the ROV with respect to the head of an Ultra Short Base Line (USBL) subsystem, mounted on a service vessel, whose position in the terrestrial coordinate system was obtained by a DGPS device. In this way, data acquired in form of pictures and acoustic images have been related to points and areas of the *physical map*. In order to guarantee a satisfactory level of accuracy in data association (that is: in associating pictures and acoustic images to geographic locations), the automatic Navigation, Guidance and Control (NGC) system of the ROV has been enhanced with a module for the real time managing of the data flow coming from the USBL/DGPS positioning system, the on-board camera and video-camera, the on-board imaging sonar (environmental data), the depth meter, the compass and the Inertial Measurement Unit (IMU) (navigation data) and for synchronization of data recording. This has been obtained by employing an hardware architecture consisting of a PXI/FPGA unit, devoted to low level control and data acquisition tasks, and of a PXI/PC unit, devoted to high level supervision tasks and to Man/Machine interface, that exchange data via TCP/IP technology. The software control programs have been developed in the LabView environment.

Due to safety reasons related to the presence of divers in the surrounding, during the survey, the ROV has been guided in the horizontal plane, while the control of depth has been delegated to the automatic NGC system. Pictures and correlated acoustic

images of the sea bottom have been taken from an average distance of 3m, at a frequency that assures a complete coverage with overlapping of the explored area. In addition to the on-board video-camera, a high definition camera mounted on the ROV has been employed to take additional still pictures, particularly in presence of archaeological features of interest.

In a following off-line phase, environmental data and navigation data have been used to generate information in form of JPEG/EXIF files as well as XML files. Such information can be exploited, first of all, for adding texture to the physical map of the site, by pasting on it low-definition pictures obtained from the on-board video-camera. In this process, navigation data can be used to orient pictures, while acoustic images and derived measurements can be used to scale them, as well as to validate morphological features of the physical map. High definition images can, then, be used to add information to selected location and to allow zoom operations on the map.

The analysis of the data gathered during the mission shows that the procedures developed for performing the various activities guarantee a satisfactory level of efficiency, efficacy and quality. For this reason, they can be viewed as a suitable basis for formalizing a set of best-practices, to be further validated in future missions.

2. PROBLEM DESCRIPTION

The problem considered in the sequel concerns the design, testing and development of a set of procedures and best practices for collecting data from underwater archaeological sites by employing robotic vehicles and automatic devices under the supervision of archaeologist and engineers, possibly in cooperation, under some circumstances, with divers. The kind of data one wants to get consists, essentially, of a set of geo-referenced pictures in photogrammetric quality and of acoustic images of a portion of the sea bottom, while navigating above it. Geo-reference should be accurate enough to allow the construction of a 3D model of the explored area in a virtual environment with a specified level of precision. This, in particular, means that pictures and sonar data must provide a complete coverage of the area of interest and that the position and orientation of cameras and sonar, with respect to a geographic coordinate system, must be evaluated and recorded at every shot and ping.

An important characteristics of the approach that has been followed is that of employing equipments of moderate cost, which are available on the market and whose use is based on the efficient integration of existing technologies. This choice aims at making accessible the methods and techniques that will be developed in the project to a large community of marine archaeologists, without the need of affording large, in some case prohibitive, costs for deep water investigations.

Underwater vehicles, either remotely operated (ROV) or autonomous (AUV), can be employed to carry cameras and sonars and navigation sensors (like compasses, depth meters, inertial measuring units, inclinometers), together with acoustic positioning systems, can be used to evaluate their orientation and location. The problems are in navigating the vehicles with the required accuracy over the site and in acquiring and recording in a synchronized way a large number of data from heterogeneous sensors.

Due to their manoeuvrability and easiness of use, small work-class ROVs are suitable for taking close range pictures and acoustic images on relatively small areas, whose interest, from an archaeological point of view, has already been ascertained. On the other hand, AUVs are suitable for preliminary, global explorations of large, partially unmapped from an archaeological point of view, areas.

3. WORKING CONDITION AND EQUIPMENT

In the mission performed in September 2006 in the proximity of Pianosa Island, in the Tyrrhenian Sea, the site to be explored was an already known one. The site was located at a depth of about 35m, on an almost flat sea bottom, and it covered an area of about 50m^2. Beside the archaeological interest – the site contains a large number of amphorae of Roman origin – that location was chosen in order to have the possibility to employ divers in cooperation with ROVs, so to compare potentialities and to test check manually the work done by automatic devices.

The ROV was operated from a support vessel, moored at three points on the site. The ROV is a small class DOE Phantom S2, equipped with two horizontal main thrusters and two vertran ones, that control four degrees of freedom. The on-board navigation sensory system consists of a depth meter, a compass and an inertial measuring unit (Crossbow DMU VGX) that evaluates linear accelerations and angular velocities along and around three axis. In the present application, the IMU has been employed mainly to evaluate the ROV pitch and roll. Pitch and roll data have been used to construct an artificial horizon that enhances the situation awareness of the operator and to evaluate the ROV attitude during operation. The ROV carries a 3CCD PAL video camera, a Nikon D2Hs camera with 4.1 mega pixel 'JFET sensor', capable of capturing eight frames per second, and an imaging sonar Kongsberg-Symrad MS 1000, whose head generates a conic beam of 2.7°. Both the cameras and the sonar have been mounted in a downward looking configuration, so to picture the sea bottom.

The underwater acoustic positioning system consists of a Sonardyne Scout USBL system, whose transponder was located on the support vessel. The position of the transponder in geographical coordinates is determined by a DGPS device with an accuracy of about 1m. The position of the ROV, in a Cartesian coordinate system having the transponder at the origin, the Z axis oriented downward along the vertical, the X axis pointing northward and the Y axis pointing eastward, is evaluated by processing the acoustic signal coming from a beacon on the ROV itself and received by the transponder. The information about the position is updated at a frequency of about 1Hz. Accuracy depends on various factors, but in worst case it is of about 2,75% of the distance. Information about the position is obviously acquired with a delay depending on the distance and related to the speed of propagation of the sound in water. Keeping the speed of the ROV below 1Kn and working at a distance not greater than 50m, the global accuracy in locating the ROV in the terrestrial coordinate system was normally of about 2m and of 3m in the worst case (see also (Caiti, 2002)).

The control architecture of the ROV, from the hardware point of view, integrates a standard console together with a PXI/FPGA unit and a PXI/PC unit, that communicate via TCP/IP technology. The PXI/FPGA is directly connected to the navigation sensory system of the ROV and it also receives data from the cameras, the sonar and the positioning system. The

unit acquires all the data and it takes care of the processing involved in their synchronous recording. In addition, the PXI/FPGA unit control at low level the sensory devices and the ROV thrusters. The PXI/PC unit is devoted to high level supervision tasks and to Man/Machine interface. The cameras and the sonar can be directly operated through this interface and all the other sensors can be monitored. In autonomous guidance mode, the PXI/PC processes the data coming from the sensors and, using the result of that processing, it may implement automatic closed loop guidance strategies. Alternatively, a human operator can guide manually the ROV commanding the thrusters digitally through the PXI/PC, by means of the keyboard and the mouse, instead of using analogical joysticks on the standard console. This digital guidance mode is particularly effective for the main, horizontal thrusters, whose angular speed is closed loop controlled. Switching between the PC-based control mode - autonomous or supervised - and the console-based supervised control mode is always possible, so to allow the operator to take manual control from the console in any situation.

The software for managing communication, implementing low level control and data processing has been developed in the LabView environment, that provides a wide range of programming tools and allows a rapid prototyping.

4. DATA GATHERING PROCEDURES

At the beginning of the mission, a side scan sonar was used to survey the site's area and to obtain a bathymetric map, called *physical map*. Using DGPS measurements, the physical map has been endowed with a geographic coordinate system corresponding to the terrestrial one. Accuracy in localizing features is of about 1m. The geo-referenced physical map has to be considered as a support on which additional information will be plotted.

A small portion of the area of interest has been structured by placing on the sea bottom, as markers, 15 blocks of concrete, in 3 rows of 5, spaced 2,5m in both direction. This work has been done from the surface, using divers to supervise and to direct the operation.

Before starting to collect data, the video camera and the camera mounted on the ROV have been calibrated using a procedure that employs Photomodeler ™ software. Calibration has been performed in shallow water (about 5m) with the help of divers.

To collect data, the ROV has executed a number of transects at 1Kn on the whole area and in particular on the structured area (for a total operating time of about 60h), taking videos, photos and acoustic images according to the procedures described below. During the navigation, the ROV was manually guided in the horizontal plane by an operator, using the video images coming from the on-board video camera and the information provided by the positioning system. The NGC system was entrusted to keep constant the operating depth, by implementing a simple PID closed loop control scheme on the basis of the signal coming from the depth meter. Since the sea bottom is almost flat in the area of interest, regulation of the depth allowed to keep an average distance from of about 3m.

In the above conditions, the characteristics of the video camera and of the camera guarantee that each frame covers an area of about $3m^2$, so that at least one marker is visible in every picture. The video camera takes 25 frames per second and, in order to have a complete documentation, the video stream is recorded by a VCR. One frame over 5 was acquired by the PXI/PC unit and digitally recorded. These set of frames provides a complete coverage, made of partially overlapping images, of a 3m wide corridor when the ROV moves along a rectilinear path. The sonar takes acoustic images of the sea bottom at a rate of one image every 100ms and these too were acquired and registered by the PXI/FPGA unit. The area hit by the acoustic wave generated by the sonar is a disk with a radius of 15cm, centred inside the area pictured by the video camera. Beside being recorded, the sonar data was also processed in order to evaluate the distance of the ROV from the sea bottom. This information was made available in real time to the operator through the M/M interface to help in guiding the ROV.

The shot of the high definition camera was operated manually through the M/M interface and the shot command was recorded by the PXI/FPGA unit. Pictures taken by the camera cover more or less the same area framed by the video camera and were recorded by the camera itself on its own flash memory. After the mission, the system has been modified in such a way that also these images are acquired and digitally recorded by the PXI/PC unit.

In addition to the above data, the PXI/FPGA unit acquired also the data coming from the positioning system and from all other navigation sensors, using different acquisition frequencies, according to the characteristics of the various devices.

All acquired data were recorded together with a time stamp, related to the time signal coming from the DGPS device.

5. DATA PROCESSING

Acquired data have been post processed off-line in order to get the information that will be used for constructing a 3D model of the explored area in a virtual environment.

The processing consists in constructing a set of files in EXIF format, each one including one picture, one acoustic image and a set of positioning and navigation data. Roughly, it can be described by saying that to every picture recorded by the PXI/FPGA/PC unit one associates an acoustic image and a set of measures taken by the other sensors. Association is made according to the time stamp, in the sense that to every time stamped picture one associates the acoustic image having the closest time stamp, while for other data association includes averaging or filtering procedures. In order to increase portability and usability, the same information has also been structured in a different, alternative way, following the XML format. The XML file contains the data of the various sensors, ordered in a coherent way, and a set of pointers to the various images.

In an intuitive way, each one of the JPEG/EXIF files described above represents an image of the sea bottom, together with information that, in particular, describe the position and the attitude of the (ROV and hence of the) camera at the time in which the photo has been taken and the distance from the sea bottom. These, together with calibration data, can be used to scale the picture, to orient it and to place it correctly onto the physical map we have mentioned at the beginning of Section 4. After all the available map have been scaled and correctly placed, it is possible to paste them together by using a

mosaicking technique.

It has to be noted that mosaicking may imply a limited adjustment of the position, orientation and scaling of the pictures, realizing, in practice, a sort of filtering of the positioning and navigation data on the basis of the optical ones. The mosaic gives a preliminary, “flat”, pictorial image of the explored area. The 3D shape of the area can then be re-created by adding relief on the basis of bathymetry and of depth and sonar measurements taken by the ROV on-board instruments. In this phase, the result of the mosaicking helps in fusing the bathymetric information obtained by the side scan sonar together with that gathered by the ROV on-board instruments. The result of this process is a virtual model of the explored area, consisting of a surface in a 3D space on which the mosaic is pasted.

6. CONCLUSION

The activity performed during the mission in the Tyrrhenian Sea has produced, through testing and experimentation, a valuable know-how about the use of UUV in gathering data from submerged sites of archaeological interest. In particular, it has been possible to explore the potentialities of the technology in providing a photogrammetric and acoustic coverage of areas of the sea bottom, suitable for constructing virtual 3D models. Practical procedures for collecting data have been established and suitable data format have been defined. Part of the gathered data, together with further information on the mission development, are available at www.venus-project.eu.

A second mission with similar objectives has been performed in May 2007, in proximity if the Tremiti Islands in the Adriatic Sea, at greater depth (between 50m and 60). This has allowed to validate the results in different, more demanding conditions and to ameliorate part of the procedures. In particular, the data handling software has been improved in order to generate the JPEG/EXIF files on-line, avoiding post-processing. In addition, the simultaneous use of two beacons, one to track the ROV and one to mark precise spot, has made possible a more accurate positioning and it has simplified the guidance task.

Future work will be devoted to the development of automatic guidance procedures, that may facilitate further the task of the operator, and to tests and experiments in deeper water.

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