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Short and Project Papers

Underwater Robots with Sonar and Smart Tether for Underground Cistern Mapping and Exploration

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Abstract

This paper describes the application of using a submersible remotely operated vehicle (ROV) to map and explore underground water cisterns during a series of expeditions to Malta and Gozo. The purpose of this project was to create maps of ancient cisterns located under private homes, churches, and fortresses where passageways leading to the cisterns are too narrow and dangerous for humans to enter. These cisterns were used as water storage systems for hundreds of years, and many still contained water. The small ROV that was lowered into these cisterns was equipped with a sonar module to enable the creation of maps, two cameras to record live video, a grabber-arm for interacting with objects in the environment, and a Smart Tether to record additional positioning data of the ROV. Each of these components are discussed in terms of functionality and appropriateness for use by archaeologists wishing to explore and extract mapping information from narrow water-filled caverns. Additionally, three different mapping and localization techniques are presented including 1) Sonar image mosaics using stationary sonar scans, 2) Sonar image mosaics using stationary sonar scans with Smart Tether position data, and 3) Simultaneous Localization and Mapping (SLAM) using stationary sonar scans. Each of the algorithms used in this project have benefits in certain applications. During two expeditions in Malta and Gozo, 2-dimensional maps of 32 cisterns were successfully constructed.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—Cistern Visualization

1. Introduction

This project concerns the use of an underwater robot system capable of mapping out and navigating underwater tunnel systems where alternative equipment would be too large to fit through small access points. Such cisterns can be found in the lower chambers of fortresses and churches. Archaeologists looking to study and document such systems have found it too expensive and difficult to use people. Furthermore, the human exploration of these subterranean water storage systems is limited by safety and physical constraints and could possibly result in irreversible damage to the site under study. Instead, a small underwater robot specifically a VideoRay Pro III Micro ROV [Remotely Operated Vehicle] is considered in this paper (see Figure 1).

In addition to the work presented in this paper, other relevant work has been conducted in underwater robot localization and mapping. One of the first instances includes the work done in [WWN*00] where sonar scans were used to map and track features of the environment. More recently, successful 3D tunnel mapping in underwater environments was demonstrated in [FKW06]. The mapping of marinas via underwater Simultaneous Localization and Mapping (SLAM) was successful as shown in [RRNT06]. Following this work, the most recent publications of underwater robots implementing SLAM in man-made structured environments has been studied in [RRNT07] and [RRTN08]. In these works, a mechanically scanned imaging sonar was used in combination with a line-feature extraction algorithm to gather information about the environment, and experiments were conducted in a marina in order to show feasibility of the approach.

Unlike the work in [FKW06], [RRNT06] and [RRTN08], this paper describes applications which only permit the passage of small-scale robot systems (i.e. passage opening di-

(a) (b) (c)

Figure 1: Shown in (a) is the VideoRay Pro with a sonar module and Smart Tether, along with the VideoRay control box in (b). The degrees of freedom for this robot are illustrated in (c).

ameters on the order of 0.3m). Furthermore, the ROV was equipped only with a depth sensor, compass, scanning sonar, and a KCF Smart Tether for cistern exploration.

2. Equipment

2.1. ROV Underwater Robot

The ROV to be considered is the VideoRay Pro III Micro ROV robot. An ROV is a robot that is controlled by an operator, and can be connected to the control equipment using a cable. In the case of the VideoRay, the tether is required for communication to and from the control box. This tether allows the transfer of control inputs to the robot as well as sonar measurements and live video to be received from the robot and recorded.

The VideoRay was selected primarily for its small size (i.e. 0.3m), which allows for passage and navigation through the constrained caverns and narrow access points commonly found in Malta.

The VideoRay is equipped with two forward thrusters, one vertical thruster, one forward-facing color video camera, one rearward-facing black and white video camera, and two forward-facing lights. The forward thrusters are controlled with an analog joystick, and the depth thruster is controlled through a separate dial which can be seen in Figure 1b. These thruster controls allow movement in three degrees of freedom in a local reference frame (forward and backward on the X axis, positive and negative depth on the Z axis, and rotation around the Z axis for yaw), as shown in Figure 1c. Also, the control box can be interfaced with an external computer for customized software control and processing of sensor measurements.

2.2. Scanning Sonar

The sonar to be considered is the Tritech SeaSprite. A sonar module is a device used to acquire distance measurements of nearby objects and walls. It works by sending an ultrasonic wave in a particular direction then measuring the time before the wave is reflected back from an object. Using this time of flight, the relative distance between the sonar module and the object can be calculated. The sonar module then rotates to acquire up to a full 360° scan.

2.3. Micro Manipulator

The Micro Manipulator arm from VideoRay was also used for this project (see Figure 2a). This arm allowed for gripping and retrieving objects while exploring the cisterns, as shown in Figure 2b. The arm is capable of lifting forty kilos underwater, and has a closing strength of two kilos, which gives the robot the capability to recover fairly large objects during a dive.

(a) (b)

Figure 2: Shown in (a) is the VideoRay equipped with the Micro Manipulator. The Micro Manipulator in (b) was used to retrieve a piece of pottery found at the bottom of a cistern in Gozo.

2.4. Smart Tether

The KCF Smart Tether has sensor nodes embedded in the cable which are used to determine the position of the ROV. These positions can be used to determine the scale of sonar mosaic maps in areas with few distinguishing features. Additionally, relative position data for each of the nodes can be used to determine the state of the tether in the event of snags or tangles caused by obstacles in the external environment.

2.5. Computer and Joystick

In addition to robot equipment, a laptop computer capable of running custom written C++ mapping software was interfaced with the VideoRay control box. When connected, the software recorded sonar, depth, compass, and control data to build cistern maps (see next section). Lastly, a joystick controller was connected with the laptop computer and used to drive the robot.

2.6. Equipment Integration

The VideoRay control equipment is shown in Figure 3 which includes the VideoRay control box, laptop with joystick, Smart Tether, and Smart Tether control PC. The Smart Tether control PC at ① collects Smart Tether data sent from the Smart Tether control box at ②. The ROV connects to the Smart Tether at ②, and can be controlled by the VideoRay controller at ③ or by the laptop at ④ when connected to the joystick at ⑥. This laptop is also used for data collection, and the laptop at ⑤ is used for recording video.

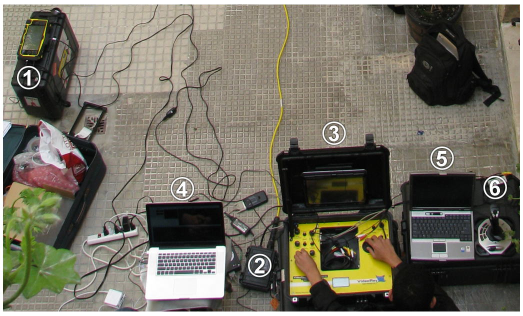

Figure 3: Shown above is the system used to navigate and collect data from the robot.

3. Experiment Description

Thirty-two different sites in Malta and Gozo were visited in total between 2006 and 2009. At each site, the ROV was initially lowered through a small opening and then down a 3-15 meter deep chute before submerging in the cistern water. As shown in Figure 4a, several layers of construction can be observed with increasing depth. A reflection of ambient light can be seen on the water's surface below as it descends down the chute (see center of image).

Once submerged, the ROV was piloted throughout the cistern, exploring any passageways and chambers. To accomplish this, operators used video from the on board camera and a joystick controller. An example of one such video image is shown in Figure 4b, where the ROV is traveling through a tight passage. Also note the water clarity in this particular cistern allowed for a reflection on the water surface (as seen in the top half of the image).

After video images of the cistern were recorded, stationary sonar scans were obtained. Each scan was taken while the ROV was sitting on the bottom of the cistern. Once a sufficient number of overlapping stationary scans were obtained, sonar scans were recorded while the ROV was in motion. Control signals, sonar, Smart Tether, depth, and heading measurement data were also recorded for use with mapping techniques, which are described in the next section.

(a) (b)

Figure 4: For each site, the ROV was initially lowered down a deep narrow chute, 4a. An image obtained while moving through a narrow passage is shown in 4b.

4. Mapping Techniques

4.1. Sonar Image Mosaics with Stationary Scans

The first approach taken was to mosaic several overlapping 360° sonar scans. Figure 5 displays an example mosaic created from six scans. Each scan on the mosaic has an obvious circle of high-strength returns indicating the robot's position within the scan. Note the high quality of the images and obvious correspondence between the scans allows a human operator to easily fuse them.

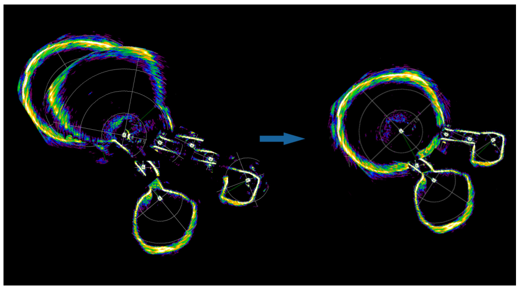

Figure 5: On the left are a collection of sonar scans obtained from a Priory in Mdina. On the right is the mosaic created from the scans.

4.2. Stationary Sonar Image Mosaics Utilizing Smart Tether

During the 2009 expedition, a KCF Smart Tether was utilized to accumulate additional position data of the ROV. The Smart Tether records the position of the ROV using acceleration, magnetic, and rate-gyro sensors. Therefore, in addition to collection several overlapping 360° sonar scans, position data of the ROV can be recorded to assist in the location of the individual sonar scans in creating a final mosaic image. Such a methodology is beneficial for cisterns that contain notably long tunnels where wall features are absent and sonar measurements can not determine the distance travelled along a tunnel. An example of this case is shown in Figure 6.

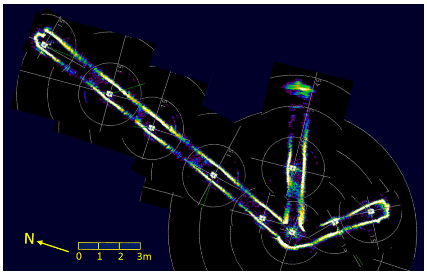

Figure 6: This sonar mosaic is of a cistern located in a priory courtyard in Rabat. This image was created through the use of the sonar scans and constructed to scale through the use of Smart Tether data.

4.3. SLAM with Sonar

One strategy that can be employed through the use of this hardware is the FastSLAM algorithm, as discussed in [COBG08]. This algorithm makes use of an occupancy grid which is used to represent the belief state of the environment [TBF05] which can be described as discretizing the cistern model into square cells of equal size. Each cell is assigned a probability that it is occupied (e.g. by a wall). An exemplary occupancy grid map for a site in an Mdina Priory is shown in Figure 7. Note the height of the cell indicates probability of occupation.

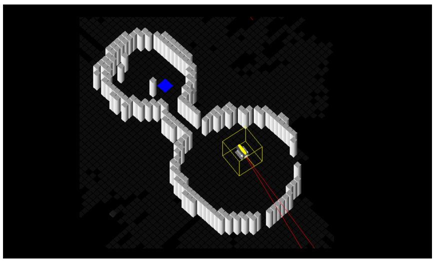

Figure 7: This is an example of an occupancy grid representing a cistern in a Priory in Mdina. The height of a cell indicates the likelihood that it is occupied by an object or a wall.

5. Archaeological Results and Future Work

As shown in the previous figures, diverse archaeological styles can be observed through the mapping techniques presented. In Figure 8a, the semi-rectangular footprint of the cistern resembles the architectural style of either the Phonecians or Romans–dating back as much as 2,300 years ago. In contrast, Figure 8b shows a two-chamber barbell-shape, which exemplifies a common shape found among the cisterns explored. Furthermore, Figure 8c displays a multi-chamber system, and lastly Figure 8d shows a distinctly rectangular floor plan, resembling that of a house or basement and likely dates more recently in the 14th century.

In the future, additional trips are being planned for Malta and potentially Italy as well. Future technological improvements will include the addition of a sonar module to be attached to the side of the ROV in order to acquire a vertical scan of the cistern to produce 3D maps.

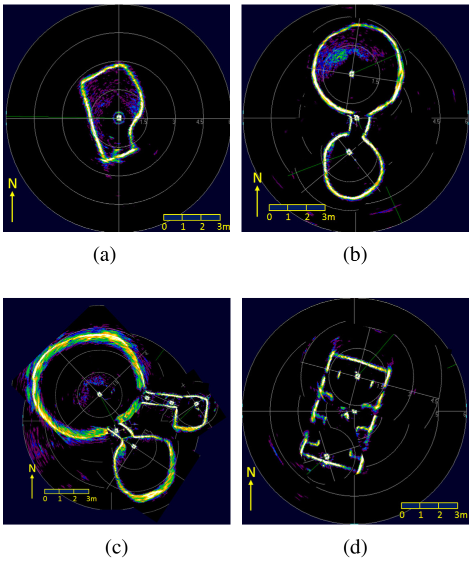

Figure 8: Shown above are sonar mosaics from several cisterns in Malta and Gozo.

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