Monitoring underwater sensors with an amphibious robot

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Abstract—The underwater domain provides a wide range of potential applications for autonomous systems. Sessile (immobile) sensor platforms can provide a sensing network to monitor a range of different underwater events. Monitoring such networks can be a challenge, however, as the sensor nodes can be difficult to monitor and the nature of the medium limits wireless communication. Here we describe an approach that uses an autonomous underwater vehicle to monitor the state of sessile sensors. A visual communication channel is established from the sensor node to the robot that can then communicate the state of the sensor to an underwater- or surface-based operator. This paper describes the basic approach and results of preliminary experiments conducted in robot monitoring of underwater sensors.

Keywords-sensor nodes; aquatic robots

I. INTRODUCTION

Maintaining an ongoing surveillance of remote or inhospitable areas is a complex task. While a single instrument platform can be an effective sensing tool, it is limited to taking measurements at only one location at a time. Clearly multiple sensor nodes can be used to provide coverage of a large area but this then leads to the problem of monitoring the sensor nodes in an effective way. In the terrestrial domain this monitoring can often be performed in a relatively straightforward fashion as standard communication systems (e.g., digital communication over standard cellular phone infrastructure) can be used. When such infrastructure is unavailable the effective monitoring of the sensor network becomes somewhat more complex. Nowhere does this problem become more difficult than when it is located underwater. The nature of the medium renders many traditional terrestrial communication channels useless, and the power and communication limits of technologies such as sonar make them unsuitable in many domains. Effective monitoring of such sessile underwater sensor networks requires the deployment of mobile devices to monitor the state of elements of the network and to develop appropriate communication mechanisms that allows the mobile element to monitor the state of the sessile nodes.

Here we explore the process of monitoring individual sessile sensors in the aquatic domain. Leveraging capabilities developed for the AQUA robot we demonstrate that sessile sensors can be positioned within an aquatic environment and serviced by an appropriately equipped visually-guided robot. The sessile sensors communicate with the mobile information-gathering platform by communicating their state information visually. Cameras onboard the mobile platform capture this information and communicate it either to a tethered operator or store the information for later processing. Experiments conducted in the open ocean near Holetown, Barbados, demonstrate the potential of the approach.

II. BACKGROUND

Sensor networks are a well-studied research field in computer science and engineering. Large-scale sensor networks have been established for both terrestrial and aquatic environments. For example, the Neptune Project [1] consists of many sub-sea sensor nodes connected by over 3000 km of powered cables. These sensor networks are deployed in order to provide a geographically disperse coverage of a range of events and find wide application. For example, sensor networks can be deployed in the aquatic domain to monitor the spread of pollutants and other contaminants, or to provide security/sentry monitoring of sensitive installations.

Terrestrial applications for sensor nodes can often leverage large-scale existing communication infrastructures in order to communicate information among elements of the network. In the underwater domain, of course, such communication infrastructure is not possible and other strategies are required. The Neptune Network, for example, uses specially laid communications cable in order to provide real-time communication among elements of the network. Such communication infrastructure has its advantages, of course. It can be used to provide near instantaneous communication of information from elements of the network. It can also be used to provide power to individual sensor nodes. But it is not without its cost. The Neptune Network, for example, has deployed over 3000 km of communication/power cabling in order to service its sensor network. For large-scale deployment, the use of specialized (wired) communication protocol is clearly impractical.

An alternative to the use of a dedicated communication conduit is the deployment of mobile communication gathering platforms in order to “service” the sessile nodes that make up the network. This leads to a range of interesting theoretical questions about when individual nodes should be serviced in order to utilize the mobile units effectively while still maintaining a timely monitoring of the underlying sensor events. At a more practical level the use of mobile units to service the sessile sensors raises questions about how the mobile and sessile units can communicate and the
difficulties associated with having a mobile unit acquire the sessile unit. This paper considers these later practical questions. Leveraging investment in the AQUA underwater robot platform we consider how sub-sea sessile sensors can communicate with a mobile sensor gathering platform and the key issues involved in developing a sensor node that can communicate over short ranges with a visiting platform.

A. The AQUA robot

Traditional aquatic robots and teleoperated devices utilize thrusters and control surfaces for mobility. In contrast, the AQUA family of robots (see Figure 1 and also [2]) is a hexapod robot capable of amphibious operation. Developed through collaboration between researchers at Dalhousie University, McGill University and York University, the AQUA vehicles are visually guided. On land, its legs provide foot-ground contact. Underwater these same legs act as flippers or fins to propel the vehicle both along the surface of the water and to depths approaching 30m. The vehicle relies on internal power and computation and can be tethered via an optical fiber tether in order to communicate with operators at or below the surface. (See [3] for details of this later capability.)

The AQUA family of vehicles support a broad range of research projects from human-robot interaction ([3] and [4]) to gait analysis and generation ([5]) to target following ([6]) to underwater environment recovery ([7]).

Operating any ROV from above the surface is hampered by the poor situational awareness available to the operator. Devices such as the AQUA family of vehicles can assume arbitrary orientation within their environment (they can manipulate their state within six degrees of freedom), yet the vehicle itself imposes limits on its dynamics. The AQUA vehicle, for example, cannot ‘sway’ and must execute complex motions in order to move laterally. One way of improving the situational awareness of the operator is to provide an operator control unit that can be submerged and operated by a diver. Such a device is described in [3]. This underwater operator control unit is shown in Figure 1 where a diver-operator can operate in close proximity to the robot. This approach can be attractive in a number of scenarios where the operator can remain relatively safe while the robot operates in a potentially more dangerous portion of the environment (deeper, in an overhead environment, in the presence of environmental contaminants, etc.) Further details on the AQUA family of robots can be found in [2] and details of the underwater tablet can be found in [3].

B. Sessile sensor

Sensors deployed in the sub-sea environment can be configured to monitor a wide range of sensor information. For the work presented here we modified a previous version of the AQUA underwater operator control unit. The AQUASensor (see [3]) is essentially a watertight housing capable of operating at depth within which a commercial tablet PC is placed. A large clear plastic port (see Figure 2) allows divers and robots operating in the water column to view display information presented on the laptop display. The housing itself contains a number of switches that can be used to communicate with the tablet PC and a fiber optic connector which are not relevant to the study here.

Although the sensor could be used to monitor a range of different environmental states, here we are concerned primarily with the issues related to communicating between
The sessile sensor. The sessile sensor is based around an earlier version of the underwater robot controller. The sessile sensor in operation displaying a communication tag.

Figure 2. The sessile sensor. (a) shows the sensor housing on the bench. (b) shows the housing operating at depth. In (b) the communication tag used to communicate the sensor status to the robot is shown.

the robot and the sensor. A time-based data stream is communicated between the sensor and the robot as it passes by the sessile sensor.

III. COMMUNICATING WITH THE SENSOR

When operating in an underwater environment communications between a sessile sensor and a surveying vehicle is limited. Wireless communication technologies are often not feasible for use underwater and wired networks are costly for large networks and can easily cause deployment issues. For this reason the sessile sensor communicates its state to the vehicle through a visual display.

The sessile sensor communicates to the mobile robot through a display based on augmented reality (AR) fiducial tags. A number of different AR tag systems have been developed including ARToolkit[8], ARTag[9], and Fourier tags[4]. The basic approach in these and other systems is the development of a set of planar tags that can be easily localized in an image, can communicate a small number of messages, and for AR-based applications, can provide relative pose information between the tag and the camera system.

Although there are many different tag systems available in the literature they are not without their individual issues. The ARToolkit tag system does not provide a standard mechanism for encoding large (hundreds) of different messages in the communications code. The ARTag system is not available as a research tool. While the Fourier tags system lacks an available software base. Given these restrictions we took advantage of the ArUco fiducial tag library that is available under BSD license (see [10]).

The ArUco library was modified to search for tags drawn from a subset of the ARTags tag system. These modified tags (see Figure 3) can be described as $10 \times 10$ arrays of square tiles each of which are either black or white arrayed on a planar surface. The outer two rows and columns of the tiles are black, and tags are chosen so that no tag is used that corresponds to a rotation of another. As the set of tags being communicated is not as large as that foreseen by the ARTag library we choose tags that are easily disambiguated from each other.

The process of extracting a tag from an image is extremely straightforward and leverages the OpenCV[11] image processing library. The process of extracting tags involves the following

1) Image is processed with the Canny edge detector to localize image edges.
2) Erosion/dilation operators are used to bridge gaps between edges.
3) Contours are extracted from the edge map and polygon approximations are constructed of the contours in the image.
4) Contours not corresponding to rectangles are eliminated and the contours are followed in a consistent direction.
5) The rectangular region of the image is warped to a standard plane and the underlying $10 \times 10$ grid is examined. Each cell of the grid should be either black or white and potential grids that do not meet this test are rejected. Furthermore, the outer two rows and columns should be black and any grid not matching this requirement is also rejected.
6) Finally, the grid pattern of the inner $6 \times 6$ grid is extracted and compared against the potential patterns being communicated. If the pattern does not exist in the planned communication channel then the pattern is rejected. Otherwise the pattern is taken as a valid communication. Note that each of the four possible
Figure 3. Subset of the communication tags used in this experiment. Communication tags are based on a modified set of ARTag tags. Each tag can be described as a 10 × 10 grid of black/white squares where the outer two rows/columns are black.

90° rotations of a pattern corresponds to the same message.

More complex processing steps are possible. For example, if it was desirable to localize the mobile robot with respect to the sessile sensor then it would be necessary to localize the communication tile more accurately once it has been identified. For the application considered here, however, such processing is not required.

Figure 4 illustrates the application of the marker identification code operating on the sessile target in approximately 30’ of water. In spite of the suspended particulate matter in the water column (aquatic snow) the target is localized and identified properly.

IV. FIELD TESTING

Although testing underwater systems in a controlled environment, such as an indoor pool, has its benefits (ease of availability, cost and safety of the divers and the equipment) the results are going to be limited to a subset of all possible observations (and are usually considered best-case scenarios). Pool trials can determine issues such as visibility problems in spite of water column distortion and issues with light reflection and refraction on the transparent cover of the sensor (causing a mirror effect). Field trials in the open ocean allow for the discovery of potentially unforeseen problems as well as provide verification of results found in more constrained pool trials. It is during this stage of system testing that the largest amount of feedback is given allowing for adjustments to be made for improved performance in future iterations. It is also the case that any system that is expected to last in an environment as unpredictable and harsh as the ocean must be able to handle realistic, less than ideal, conditions that are most readily tested for during these trials.

In recent field trials near Holetown, Barbados we deployed the sessile sensor tablet and had a nearby diver operate the AQUA robot using our third generation AQUA Tablet, although both systems were not deployed during the same dive due to logistical issues. Despite the fact that both systems were not deployed at the same time, both systems were tested under similar, non-ideal, conditions. Rainfall over the previous days had lead to reduced underwater visibility. When testing the AQUA Tablet operator interface, conditions were considerably worse as the operator, cable managers and the robot were all in the presence of a considerable surge. Notwithstanding these issues both the sessile sensor and tablet-based underwater tele-operation of the vehicle were tested successfully. The heavy surge present during the testing of the vehicle did, however, prevent the deployment of both the sessile sensor and the robot with its operational tablet as a single unit. Thus in the tests described here the robot’s onboard cameras were simulated using a standard underwater video camera.

As the robot and sessile systems were not deployed at the same time, video of the sessile sensor operating underwater was gathered by a diver using a Sony DSC Camera at depths between 20’–40’. Table I summarizes the performance of the target identification process for eight different data collection runs. For each run the video sequence was trimmed to the portion in which the target was fully in the frame and the algorithm run. For each sequence the number and percentage of correct and false target identification are reported. Summaries are also provided over all tests and also over only those tests in which at least one data point was recovered (that is, excluding tests 2-3 and 7-8).

No false target responses were reported over all tests, and...
Table I

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**MARKER DETECTION EVALUATION. PERFORMANCE IS SHOWN FOR EIGHT DIFFERENT IMAGE SEQUENCES CAPTURED OF THE SESSILE SENSOR. FOR EACH SEQUENCE THE START AND END FRAME WITHIN WHICH THE SESSILE SENSOR WAS IN FRAME WERE DETERMINED AND THE TARGET CAPTURE PROCESS RUN. THE NUMBER OF FRAMES FOR WHICH THE CORRECT TARGET WAS IDENTIFIED AND THE NUMBER OF FRAMES FOR WHICH THE TARGET WAS IDENTIFIED ARE ALSO SHOWN. PERCENTAGE CORRECT AND PERCENTAGE FALSE OF THE TOTAL NUMBER OF VISIBLE FRAMES IN THE SEQUENCE ARE SHOWN. SUMMARY VALUES ARE ALSO PROVIDED FOR ALL SEQUENCES (“ALL DATA”) AND FOR SEQUENCES IN WHICH AT LEAST ONE CORRECT ID WAS RECOVERED (“DATA > 0”) ARE ALSO PROVIDED.**

for those sequences in which the system was able to identify at least one target the average recovery rate was 57%. At capture rates in the 30Hz range this implies that on average more than 15 positive measurement of the target is made each second.

When does target acquisition fail? Prior to deployment it was anticipated that the largest visibility concern would come from the presence of aquatic snow (a high density presence of particulate matter) suspended in the water column. Although large pieces of aquatic snow obscuring the outer boundary of the tag did cause the identification of the tags to be lost momentarily, such signal loss was intermittent. Longer duration signal loss was associated with failure modes such as those shown in Figure 5.

Figure 5(a) shows refraction-related failure. Here the sessile sensor is viewed beyond the critical angle for the water-transparent-air boundary and the surface, normally transparent, acts as a reflector. Figure 5(a) is actually an intermediate output of the image processing stage of the target acquisition process and shows detected boundaries. No boundary is found of the target. Acquiring the target requires viewing the sessile sensor at angles close to the normal of the surface. This has implications for the robot attempting to acquire the sessile sensor.

Figure 5(b) shows a reflection-related failure. Here the video camera and diver are backlit and are reflected in the surface of the sessile sensor. (The sensor was placed on the ocean floor in approximately 40’ of water.) The process of marker extraction is compromised by the reflection of the camera/diver in the sessile sensor. As in Figure 5(a) the image shows a step in the extraction of the visual target. Portions of the reflected diver/camera confuse the image processing process.

V. DISCUSSION

Almost 70% of the Earth’s surface is water that supports a rich multitude of flora and fauna that, in turn, support life as we know it. This region is inhospitable to humans and monitoring even a small fraction of this area is a daunting task that is limited by the availability of technology that can withstand being submerged for extended periods of time and the costs associated with deploying and maintaining the sensor technology.
Monitoring a network of physically disparate sensors in the underwater domain presents many challenges. The underwater domain prevents the use of radio-based communication technology that finds wide application above the surface. Rather than relying on a network of wired connections the approach presented here uses an autonomous vehicle to monitor a sessile sensor node. The node communicates with the autonomous vehicle by displaying encoded messages in the form of fiducial tags. In preliminary field trials conducted in the open ocean near Holetown, Barbados, the system was deployed with the robot camera sensor simulated using a video camera in an underwater housing. Even in poor visibility conditions (for the Caribbean Sea, anyway) the target identification algorithm was able to extract and identify the fiducial markers under a range of conditions. Some conditions were found to be problematic but it is expected that the robot can approach the sensor in such a manner as to minimize the potential of these situations occurring. For nominal target viewing conditions the system was able to recognize the presented target approximately 57% of the time and no false targets were reported.

Future work will consider the use of multiple sensor nodes to provide coverage over a large area and the autonomous monitoring of the nodes by the robot. Other issues to be considered include sensing the proximity of the autonomous robot so that the sessile sensor can conserve power when the robot is not in range.

ACKNOWLEDGMENTS

The financial support of NSERC is gratefully acknowledged. The authors would like to thank all of the researchers involved in the AQUA project and the staff at Bellairs Research Institute for their support.

REFERENCES


