Maritime Surveillance in the Intracoastal Waterway using Networked Underwater Acoustic Sensors integrated with a Regional Command Center

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Abstract—Underwater passive acoustic directional sensors and Seaweb through-water networked acoustic communications are implemented in the Intracoastal Waterway at Morehead City, North Carolina on the U.S. eastern seaboard. The objective is to demonstrate capability for first-alert protection of a high-value port facility against asymmetric threats that intelligence sources indicate are arriving via watercraft. Battery-powered acoustic sensors are rapidly deployed at widely separated chokepoint locations in shallow 5-10 meter water. These sensors autonomously detect the passage of a maritime vessel and generate a contact report indicating time, location and heading of the target. Seaweb through-water acoustic communications delivers the contact report via a scalable wide-area underwater network including multiple acoustic repeater nodes and a radio/acoustic communications (Racom) gateway buoy. The Racom gateway telemeters the contact report via Iridium satellite communications to an ashore command center with low latency. The in situ acoustic detection is corroborated using shore-based video surveillance to classify the contact as friendly or actionable.

Keywords— Seaweb, telesonar, underwater acoustic sensor, autonomous processing, maritime domain awareness, data fusion, maritime surveillance, acoustic communications, operational adaptation, Racom.

I. INTRODUCTION

Maritime points of entry, much like airports and borders, are the front lines in our defense against terrorism, smuggling, and other international crimes. Bays, harbors, and ports are especially vulnerable to illegal operations because of their large area and the difficulty of monitoring them. Increased vigilance of these maritime points of entry is required.

Automatic Identification System (AIS) has proven useful for reporting legitimate traffic, but this voluntary tagging of vessels does not identify asymmetric and irregular (i.e., “dark”) maritime threats, and is susceptible to false reporting by malicious vessels.

Effective maritime surveillance requires the use of in situ sensors to independently detect the passage of watercraft and to report these contacts to a regional command center for data fusion with both AIS and remote sensing systems deployed in space or ashore.

We propose the use of distributed passive underwater acoustic sensors with autonomous processing for detecting maritime targets, as depicted in Fig. 1. These underwater acoustic sensors are derived from decades of U.S. Navy research in anti-submarine warfare (ASW). Their utility against relatively noisy surface vessels is very good. Furthermore, we propose the use of Seaweb through-water acoustic communications to deliver actionable contact reports to a regional command center in near-real time.

As a demonstration, we implement such a capability as part of the ONR Operational Adaptation (OA) Integrated Technology Demonstration (ITD-1) Developmental Test #2 (DT-2) during February 2010 at Morehead City, North Carolina, USA. The exercise scenario is described in Fig. 2. The strategy here is that the underwater sensor network will alert the regional command center to evaluate the contact with respect to other intelligence, surveillance and reconnaissance (ISR) data, and to cue ashore or overhead video assets. We exploit the proximity of the shoreline to implement visual surveillance for coincident observation of maritime targets.

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Initially, individual systems, such as the Seaweb sensor network, are deployed and shakedown tests conducted. This is followed by an integration period when the disparate sensor inputs are fused to produce an overall operational picture. Finally, a series of exercise events are staged to evaluate the effectiveness of each system and the utility of the integrated maritime surveillance capability.

The sensor autonomously and continuously analyzes the acoustic data to detect and classify potential signatures of radiated sound from vessels. As seen in Fig. 4, the processing consists of both a broadband and narrowband analysis. The broadband analysis indicates the presence of a transient (over the period of a few minutes) noise source, while the narrowband analysis classifies whether or not that noise source is of interest. The narrowband analysis infers engine, transmission, and propulsion characteristics of the sound source, such as engine rpm, number of cylinders, stroke, transmission gear ratio, and number of propeller blades. If these characteristics match specified criteria derived from a library of known target signatures, then the sensor generates an alert message that is transmitted via the Seaweb underwater acoustic network to the Racom gateway buoy.

II. IN SITU MARITIME SURVEILLANCE

A. Passive acoustic directional sensors

The acoustic sensors are designed to provide persistent, autonomous detection and classification of targets of interest and to report these contacts via the Seaweb network. The sensors operate as stationary nodes on the seabed with a maximum operational depth of 200 m. The sensor node can be deployed via a detachable tether or allowed to freefall to the bottom. Recovery is via free ascent and is initiated by jettisoning a drop weight using a remote-controlled acoustic release. Each sensor node weighs 70 kg in air, and is 0.3 m in diameter and 1.8 m in length. The package is normally deployed with a 23-kg drop weight that produces a 11-kg negative buoyancy in water. For this exercise, the operational area is known to have significant tidal currents so the standard drop weight is augmented with a 0.6-m by 0.6-m steel plate to provide additional stability.

Fig. 3 demonstrates the primary components of the sensor node. These include (1) a directional acoustic sensor with flow shield, (2) an electronics module containing a low-power microcontroller, DSP, analog-to-digital converters, and telesonar modem, (3) a battery module containing 2 primary-cell lithium battery packs, (4) a recorder module containing acoustic data and microcontroller console recorders, (5) an acoustic modem transducer, (6) a drop weight with acoustic releases, and (7) a flotation collar.

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B. Seaweb through-water network

Enormous strides have been achieved in the development of underwater sensor networks for ASW and other oceanographic applications [1]. For this exercise we apply U.S. Navy Seaweb technology to enable maritime surveillance. As illustrated in Fig. 5, Seaweb sensor networking is motivated by a requirement for distributed wide-area sensing in littoral waters, typically 50-200 meters in depth.
Seaweb networking firmware is implemented on commercial off-the-shelf (COTS) telesonar modems produced by Teledyne Benthos, Inc. such as that pictured in Fig. 6, left [2]. Seaweb firmware replaces the COTS telesonar modem firmware to enable reliable end-to-end communications from a source node to a destination node along a network route. Telesonar repeater nodes are deployed in the manner shown in Fig. 6, right, permitting ease of deployment and recovery.

After a set of telesonar-equipped nodes is deployed, the Seaweb network routes are autonomously initialized through a network discovery process [3].

Figure 6. On the left is a view of the COTS telesonar acoustic modem, a U.S. Small-Business Innovative Research (SBIR) product commercially available from Teledyne Benthos, Inc. The deployed telesonar repeater node shown on the right includes a clump weight, an acoustic release, a telesonar modem, and a subsurface float. Deployment of the telesonar repeater node is accomplished by simply dropping the assembly overboard at the desired location. Recovery of the node is accomplished by acoustically releasing the expendable weight, allowing the subsurface float to bring the repeater node to the sea surface.

C. Racom gateway buoy

In this exercise we anchor the solar-powered Racom gateway buoy seen in Fig. 7, left, at a site adjacent to the Morehead City Coast Guard Station. This particular buoy is one of six built by the U.S. Navy for offshore deployment in strong currents and high sea state. For future long-term operations at this site, we recommend Racom implementation using existing USCG infrastructure exemplified by the navigation buoy shown in Fig. 7, right. Racom implementation on this USCG navigation buoy was demonstrated in the San Francisco Bayweb 2009 trials.

The Racom gateway buoy includes a subsurface telesonar modem and a topside Iridium modem. Other radio types have been implemented previously, including cellular telephone modem and line-of-sight packet radio. Iridium satellite communications has the advantage of unrestricted connectivity to remote sites such as the regional command center established for this exercise.

Figure 7. Racom buoy implemented as a deployable solar-powered buoy and on a USCG navigation buoy.

III. DEPLOYMENT OF SEAWEB SENSOR NETWORK

In this exercise, we apply Seaweb technology in adverse environmental conditions. Water depths are 5-10 m, tidal currents are up to 2 m/s (4 knots), and underwater ambient noise is elevated by winter weather conditions. In addition, acoustic propagation is impaired by variable stratification of fresh runoff and salty ocean water. An unexpected disadvantage is the presence of a large dredging vessel during daylight hours, elevating the ambient noise levels and placing our deployed equipment at risk. To our advantage is the fact that February sees only moderate recreational boat traffic.

As an initial test, the sensors (nodes 18, 19) and the Racom gateway buoy (node 1), are deployed to form a simple Seaweb network where each sensor node communicates directly to the gateway node via a single telesonar link. The purpose of the initial deployment is to characterize the sensor performance in a very shallow (typically < 6 m), high-current environment and to demonstrate telesonar communications over short ranges. In addition, the sensor placement in this arrangement permits simultaneous acoustic detection of targets at both sensors which is helpful for diagnostic testing. Watercraft of opportunity and controlled runs with a support vessel serve as experimental targets in the initial testing. After the initial period of testing, we enlarge the network by adding 6 telesonar repeaters (nodes 11, 12, 14, 15, 16, 17) and begin testing Seaweb networking in parallel with further acoustic sensor testing. With a telesonar modem deck box deployed from the support vessel, we evaluate telesonar communications among the deployed nodes. The sensor nodes continue to communicate directly with the gateway node during these shakedown tests.

To aid in the understanding of the acoustic sensor performance and the acoustic communications performance, we measure the sound-speed profile (SSP) and its variability in time and space. We enter SSP data into a propagation model to interpret the environmental influence on the underwater acoustic signals. This model is a planning tool for the final laydown of the network nodes.

Following evaluation of the sensor and communication shakedown tests and aided by the propagation model, we
reconfigure the network geometry in preparation for the maritime surveillance exercise. The final arrangement of sensors, telesonar repeaters, and gateway buoy is charted in Figs. 8 and 9. In this configuration, the sensors act as tripwires against possible targets of interest approaching the port facility from the west along the Intracoastal Waterway or from the southeast through Beaufort Inlet. Due to security constraints, the Racom buoy remains anchored in close proximity to the Coast Guard station. Sensor 19 has direct telesonar communications with the gateway buoy while sensor 18 communications must pass through a route of 7 telesonar links prior to reaching the gateway. The route distance between sensor node 18 and gateway node 1 is 4.3 km.

IV. PERFORMANCE OF SEAWEB SENSOR NETWORK

The Seaweb sensor network performance is evaluated during 22-24 February, 2010. During this time period boats instrumented with GPS recorders are driven past the sensors at various ranges and the alert messages generated by the sensors are recorded. The GPS recordings were analyzed after the exercise to correlate the target boat approaches with alert messages. The target boats are a 7-m work boat with twin Yamaha 150-horsepower 4-stroke outboard engines, and a somewhat larger boat with twin inboard diesel jet drives.

There are a total of 34 target events during this time period. The sensors generate an alert message on 29 of these 34 opportunities, for an alert percentage of 85%. Fig. 10 shows the number of events as a function of the range at their closest point of approach (CPA). As can be seen, all of the alerts occur for CPA ranges of 0.2 km or less, and 4 out of the 5 missed events (events for which an alert was not generated), occur at CPA ranges greater than 0.3 km. We infer that for this specific environment and target set, a CPA range of 0.2 km is necessary to obtain a narrowband classification.

The alert messages contain, among other things, the time of initial broadband detection. Correlating this time with the GPS tracks of the target boats, we determine the range of the targets at the time of initial broadband detection. Shown in Fig. 11 is the distribution of these initial detection ranges. The median initial detection range is 1.1 km, which is significantly greater than the 200-m CPA range required for narrowband classification.

Figure 10. Statistical analysis of the target opportunities during the 3 test events shows that the acoustic sensors perform well against targets having closest point of approach (CPA) within 200 meters. Within this range, the probability of detection is $P_d = 0.97$.

Figure 11. Analysis of recorded data reveals that the sensors begin to track contacts at ranges significantly greater than the CPA ranges. This is a significant result given the shallow-water environment and adverse acoustic conditions.

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The sensors log various information on internal recorders, including the time each alert message is transmitted. The internal clock of each sensor is synchronized to UTC prior to deployment. The Racom buoy also logs the receipt of the messages. The time difference is a measure of the communications latency, or time required to transmit the messages from the sensor node to the Racom gateway node. Shown in Fig. 12 are the measured latencies from sensor 18 to the Racom buoy. With 6 repeater nodes in the route connecting sensor 18 to the Racom, the median latency is 113 s. Larger than normal latencies occur for 3 consecutive alert messages and are the result of increased channel noise levels, either from wind or boat traffic.

V. INTEGRATED MARITIME SURVEILLANCE

A. Regional command center

By virtue of the Iridium satellite link modem installed on the Racom gateway buoy for this exercise, the command center can be anywhere in the world. In actuality, the command center site is a compound of buildings shown in Fig. 13 at a military air field 32 km from the deployed Racom buoy. Converging here are the data links and command and control functions for the various systems participating in the exercise. Although this is an exercise involving many new technologies, a realistic operational tempo is maintained on the watch floor during the demonstration phases.

B. Deployment of video surveillance sensors

The exercise includes aerial video surveillance sensors installed on manned and unmanned aircraft, but these assets are grounded for the duration of the exercise because of a logistical issue. Nevertheless, a set of Rapidly Deployable Video Analysis (RDVA) camera units such as that shown in Fig. 14 provide live video feeds to the command center and prove to be effective during daylight conditions. Fig. 15 shows that RDVA cameras can be operated at fixed stations or mounted on mobile platforms such as an automobile. Three RDVA cameras are positioned with views of the water corresponding to the detection footprints of the underwater acoustic sensor nodes.

C. Cueing of deployed video surveillance system

Acoustic alerts delivered by Seaweb are posted to the command center chat room. These alerts cue the RDVA camera operators to bring up video feeds for the camera corresponding to the deployed acoustic sensor as seen in the screen capture displayed in Fig. 16.
D. Exercise events

Three maritime exercise events are staged by hypothetical adversaries. The goal of these events is to detect anomalies and anomalous behavior, thereby accelerating our ability to observe, orient, decide, and act.

Seaweb performance is very good during these events, as evidenced by the statistics presented in Figs. 10-12. Acoustic alerts serve to cue ashore video systems which successfully distinguish maritime threats from normal boating activity, as shown in Figs. 17 and 18. The fused sensor data provides the basis for decision at the regional command center to task local law enforcement to action.

Two of the exercise events are scripted tactical vignettes, and one is unscripted. The first event leads to a boat takedown and seizure of inert improvised explosive device (IED) materials. The second event leads to interception of a dummy weapon of mass destruction (WMD) trigger device. The third event is an unscripted meeting and resupply of insurgent leadership which is disrupted as their vessels reach dock.

VI. CONCLUSIONS

Underwater acoustic sensing is shown to be effective for surveillance of surface vessels in a very shallow, noisy maritime environment. This result is impressive given that the demonstrated sensors are optimized for detection of targets in littoral waters (50-200 meters). In addition, acoustic communications and networking are also shown to be effective in these shallow-water conditions. Major benefits of networked distributed underwater sensors are:

- Deployable, retrievable, and relocatable network nodes;
- Superior sensor performance (compared to non-distributed sensors);
- Scalable and configurable architecture;
- Persistent and survivable autonomous nodes;
- Clandestine posture;
- Wireless infrastructure;
- Interoperable and heterogeneous network (i.e., various sensor types and vendors can be combined);
- Proven hardware and software;
- Autonomous in-node processing;
- Timely contact reports; and
- Cost effectiveness.

We recommend that Seaweb-enabled distributed surveillance sensors be exercised more aggressively in waters that have previously been considered too adverse for underwater surveillance. Furthermore, we recommend emphasis be given to integrating underwater sensors through the common architecture afforded by Seaweb. Finally, we highlight the operational utility of underwater sensing in combination with video surveillance.

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REFERENCES