Results of OEX Missions Using a Chirp Sidescan Sonar with Fuzzy Mine Detection Algorithms

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Introduction

A 850 kHz chirp sonar was designed and constructed to provide AUVs with the capability of automatically detecting mines lying on the seabed. Automatic detection of mines is performed in real time using a chirp sidescan sonar running fuzzy image clustering procedures which search acoustic backscattering for shadows cast by bottom mines. The search technique does not require training, so it can be utilized in unknown environments. An energy detector that integrates the squared envelope of the acoustic signal over the predicted length of an acoustic shadow, is used to detect drops in backscattering associated with acoustic shadows. The algorithm detects a shadow when the average backscattering level drops 6 dB below the average scattering noise, a range dependent parameter. The mine-like target membership of a sequence of shadow detections depends the horizontal and vertical offsets between shadow detections. The target height and length, determined from the acoustic shadow, are used to classify the target as mine-like. The length, height and location of the mine are measured by the sonar processor and reported to the AUV host via a serial link in real time. An image of the mine can also be requested by the AUV for transmission via modem to shore or to a support ship.

System Description

1) Hardware Description

The 850kHz chirp sidescan sonar consists of a PC based sonar processor contained in an underwater canister mounted inside the nose section of the Ocean Explorer (OEX) AUV and two sidescan arrays mounted on the side of the AUV as shown in Figure 1. The operating frequency of 850 kHz was selected to ensure that the wavelength was short enough so that scattering from sloping target surfaces could be used to provide detailed target images while avoiding the 1.2 MHz DVL(doppler velocity log) operating band. The arrays have a bandwidth of approximately 40 kHz. A 466 MHz Celeron processor card and a 16 bit data acquisition card are mounted in a passive backplane inside the bottle. The Celeron processor performs the correlation processing, image construction and target detection in real time. The sonar uses an external 48 VDC battery for power. It communicates with the AUV via a LonTalk to serial (neuron) interface card mounted inside the sonar canister. As targets are detected, the PC transmits target data out the serial port on the Celeron processor board to the neuron card which relays the data to the AUV LonTalk communication system. The acoustic modem reads the messages off the LonTalk network and relays them to the surface ship as shown in Figure 2. The shipboard display provides target position data and a target quality factor for each mine-like target detected by the sonar.
2) Signal Processing and Target Detection
The signal processing flow diagram in Figure 3 starts with the processing of acoustic returns measured by the sidescan array and terminates with the reporting of mine-like targets to the surface ship. The sidescan array output is sampled at 100 kHz (greater than twice the acoustic bandwidth) and is filtered by a correlation processor. The correlation processor continuously generates the envelope of the acoustic signal. The envelope is corrected for two way transmission loss and is added to a seabed image matrix. The envelope data is averaged over approximately 100 pings in 30 range intervals to calculate an average scattering function. The envelope of the most recent ping is compared to the average scattering function at each range increment to determine the presence of an acoustic shadow. The algorithm assumes a shadow exists if the average value of the envelope is less than 6 dB below the average scattering function at a given range. The time duration of the running average detection filter is equivalent to the duration of an acoustic shadow for the case of the shortest target of interest. When the shadow is detected, the end points of the shadow segment are stored for subsequent processing in the fuzzy clustering routine. Figure 4 shows the shadow of a concrete block before and after shadow segment detection.

As each new shadow segment is detected, a fuzzy clustering routine builds a target shadow by attempting to group a newly detected shadow segment with other shadow segments in the same neighborhood. The distance in transmissions between shadow segments and the across track overlap of shadow segments are used to determine the membership of the segment in a cluster. The membership of a segment in a cluster is determined using the two membership functions shown in Figure 5. Note that when segments in successive pings are not overlapping in range, the overlap membership is zero; conversely, when one of segments is overlapping both ends of the other segment, overlap membership is one. The fuzzy membership handles intermediate cases. The group membership of a newly detected shadow segment is given by

\[ \mu_{\text{group}} = \mu_{\text{overlap}} w_{\text{overlap}} + \mu_{\text{distance}} w_{\text{distance}} \]

where \( \mu_{\text{overlap}} \) and \( \mu_{\text{distance}} \) are the overlap and distance membership functions, respectively and \( w_{\text{overlap}} \) and \( w_{\text{distance}} \) are the respective weighting factors. The sum total of the weighting factors equals 1.

When the membership of a shadow segment in a group exceeds a threshold, the segment is assigned to the group. If there are no new assignments to a group of shadow segments, the construction of the target shadow is finished. The height and length of the target is measured from the shadow segment location data stored for each target shadow. If a shadow matches the height and length of a mine-like object, the shadow information is stored in a database with an image of the mine. Simultaneously, the target position data is sent to the AUV host via the LonTalk network which relays the data to the surface ship via the acoustic modem.

**Description of Experiments**
The automatic mine detection algorithm was tested in real time on three missions using the 850kHz chirp sonar mounted in an OEX AUV, called Drake. The first mission occurred on June 9th, 2000 off the coast of Dania Beach, Florida during the FBE (Fleet Battle
Experiment) workup. The sonar data set contained 150,000 m$^2$ of seabed imagery. The second and third missions occurred on August 25$^{th}$, 2000 and September 5$^{th}$, 2000 off the coast of Panama City, Florida during FBE. On August 25$^{th}$ and September 5$^{th}$, 40,400 m$^2$ and 202,500 m$^2$ of seabed area was covered by the AUV. During the search, the AUV operated at a speed of 2.5 knots with an altitude varying from 3 to 5 meters. Sonar range was 15 meters. Figures 6 through 8 contain sidescan images and photographs of Mk 63, Manta, and Rockan mines that were detected during the AUV missions. Note that the Rockan mine generates a weak acoustic echo at some target aspects. Consequently shadow detection is the only reliable method for detecting mines with low target strengths and is the basis for the mine detection approach taken in this research.

Results
During the FBE and FBE workup, mine-like targets appeared 64 times in the acoustic imagery. The sonar detected all mines and reported 23 false alarms within the search range. During the mission, the sonar reported to the support ship via modem significantly more than 64 false alarms because the detection algorithm was set to start at range zero where shadow lengths are approximately one sample in length resulting in a noisy output from the energy detector. Omitting the false detections under the vehicle, a total of 64 false alarms were received during the 3 hours and 19 minutes of mission time. About 70% of the false alarms were caused by fish swimming alongside the sonar and casting mine-like shadows on the seabed. Planned improvements to the detection algorithms are expected to reduce the false alarm rate by a factor of 2 to 4.

The effect of changing the clustering threshold (used to group shadow segment detections within a target shadow) on the number of detections false alarms was determined by processing data from three mine hunting missions. Table 1 and Figure 9 show the effect of raising the shadow segment clustering threshold above the value of 0.699, the setting used during the AUV mine hunting missions. During the 3 hour and 19 minutes of total sonar mission time with the detection threshold (mine-like target membership) set to 0.699, all mines were detected with 23 false alarms. During the simulations, the detection algorithm commenced processing data at sonar ranges where the Manta mine starts generating acoustic shadows; that is, the algorithm ignored the data under the AUV where shadows do not exist or are too short to detect. Figure 9 shows that reducing the threshold below 0.7 dramatically decreases the percentage of targets detected. Most of the false alarms were caused by fish swimming along side the AUV causing mine-like shadows in the imagery.

Conclusion
The 850 kHz chirp sidescan, mounted in an OEX AUV, and executing real time mine detection algorithms, conducted mine hunting missions during the FBE workup off Dania, Florida and the FBE off Panama City, Florida. The sonar reliably detected the bottom mines and reported mine positions to the surface ship in real time via an acoustic modem. Future work involves sending mine image snippets stored on the sonar hardfile to the surface support ship allowing real time viewing of mine images with target position data.
Figure 1 Top - Autonomous underwater vehicle Ocean Explorer (OEX)
Bottom – 850kHz sidescan array housing mounted on side of OEX AUV.
Figure 2. Mine detection data flow from AUV mounted chirp sidecan sonar to shipboard display
Figure 3. Real time signal processing and target detection performed by chirp sidescan sonar processor
Figure 4. Sidescan image of concrete block showing detected shadow segments which are grouped together using a fuzzy clustering routine.
Figure 5. Group membership functions for shadow segment overlap and shadow segment separation are used to assign a detected shadow segment to a group of segments. High membership values for segment overlap and segment separation are requirements for assigning a shadow segment to the cluster of shadow segments that make up a target shadow
Figure 6. Sidescan image and photograph of Mk 63 mine
Figure 7. Sidescan image and photograph of Manta mine
Figure 8. Sidescan image and photograph of Rockan mine
<table>
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<tr>
<th>Detection Threshold, T</th>
<th># of Detections</th>
<th># of False Alarms</th>
<th>Detection %</th>
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Table 1. Results of simulated missions using FBE and FBE Workup data where shadow segment clustering threshold was varied showing its effect on detection and false alarm rates.
Figure 9. Percentage of mines detected versus the number of false alarms per 1000 sq meters of sonar coverage area. Fish swimming adjacent to the AUV cast large mine-like shadows on the seabed causing most of the false alarms.