Collision Avoidance Passive Sonar

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Abstract— **Open-ocean deployment of unmanned underwater vehicles (UUVs) or unmanned surface vehicles (USVs) reveals a problem that such unmanned robots are ill-equipped to handle, namely avoiding collision with approaching surface shipping. This danger may be reduced if the robot carries a radar and/or has access via radio to commercial Automatic Identification System (AIS) information. However, radars are expensive and both radars and radio can only be used above the water, while AIS status is not always broadcast by passing shipping.**

An alternative solution may be found through the use of underwater acoustics whereby a sonar system determines the direction of arrival for a surface ship based upon its own radiated noise. The efficacy of this method lies in the use of as much of the radiated frequency spectrum as is practical, hence a broadband sonar is preferred.

Ultra-short baseline (USBL) is a well-known method for estimating the direction of arrival for known narrow band acoustic signals. Our method modifies USBL algorithms to support direction of arrival estimation for any wideband source of acoustic energy without *a priori* knowledge of the specific temporal or spectral characteristics of the signal. The method requires an array of several listening hydrophones spaced a pre-determined distance apart in a known geometry. The spacing among hydrophones is dictated by the upper limits of the frequency band, while the available bandwidth then is dictated by mathematical artifacts that develop if the band is too wide. For example, a frequency band of 1600 Hz to 3600 Hz can be accommodated with a hydrophone spacing of approximately 20 cm, but frequencies below about 1600 Hz will cause artifacts in the signal processing. Bandpass filters are necessary to preclude the device from receiving lower frequency signals.

I. Introduction

Unmanned platforms on or near the sea surface are at danger of collision with other shipping, especially if the platform lacks radar and/or the other vessel is not radiating its Automatic Identification System (AIS) status. Fortunately, most surface vessels utilize some form of propulsion system which generates broadband acoustic energy. We can make use of this energy to estimate the direction of arrival (DOA) if we have a system properly tuned for the frequency band of the energy.

The radiated energy of a surface vessel typically extends from a few hundred Hertz to well in excess of 10 kHz, but the spectral location of the dominant portions of the energy are specific to the class, loading, speed, and manoeuvring of the vessel. As an example, Figure 1 shows a typical radiated noise spectrum from a utility craft operating at a moderate speed of approximately 12 kts. One observes the strong frequency-dependence of the energy, with the dominant energy located below 5 kHz.

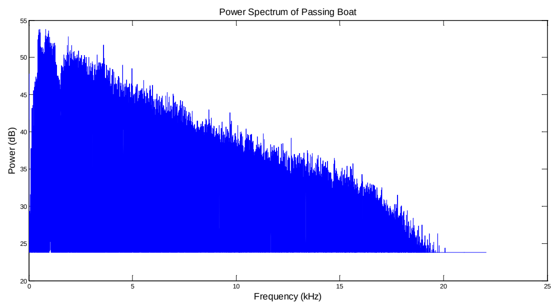

Figure 1. Frequency Spectrum of the radiated noise from a passing boat

Any portion of this spectrum is useable, provided it is sufficiently stronger than the ambient noise, However, the lower the frequency we tune for, the greater the distance obtained due both to lower attenuation and higher signal to noise ratio (SNR).

Teledyne Benthos has developed a (patent pending) method for determining the DOA of energy such as that shown in Figure 1. This method stems from our existing commercial wideband USBL technology. The method requires no detection or classification algorithms, although the latter would be highly beneficial in the future. Bearing accuracy varies with SNR and frequency, but is on the order of 5 degrees or less.

Section 2 describes the DOA estimation algorithm and discusses hardware issues. Section 3 describes some recent experiments, and section 4 provides concluding remarks.

II. PASSIVE BEARING DETECTION

Teledyne Benthos has developed the Passive Bearing Detector (PBD) which utilizes a DOA estimation method similar to ultra-short baseline (USBL), but modified for wideband signals. As with conventional, narrow band USBL, we relate the phase differences among a group of closely-spaced hydrophones to an equivalent time-of-arrival problem with a unique solution for both azimuthal and vertical DOA. Phase is obtained via broadband cross-correlations among the hydrophones.

We "tune" the PBD by separating the hydrophones to accommodate the frequency band of interest. For example, for a frequency band of 9 – 14 kHz, hydrophone spacing in a tetrahedral shape is approximately 5 cm, while a frequency band of 1600 Hz to 3600 Hz can be accommodated with a hydrophone spacing of approximately 20 cm. There is always a lower frequency edge to the band below which artifacts will appear in the DOA estimation. The algorithm is well served by a good quality bandpass filter to isolate the band of interest from broader signature components, as well as to isolate the unit from out-of-band interference.

Figure 2 shows one realization of a hydrophone geometry suitable for the PBD applications.

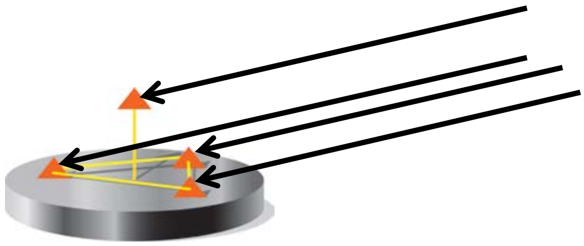

Figure 2. A tetrahedral geometry appropriate for PBD applications

As with any interferometric system, the PBD is only suitable for processing a single source of energy at one time. If two or more energy sources are received at the same time, the PBD will respond with DOA estimate somewhere between the sources – depending on relative signal strength.

The PBD, in its present configuration, will make estimates of DOA regardless of the presence or absence of a dominant noise source. It is a "dumb" system which simply estimates DOA based on whatever noise is present at any moment. However, if a human operator observes a display, the bearing estimates will be relatively random in azimuth – until a source comes into range, at which point the DOA estimator will be captured, such that it focuses on that source. Without foreknowledge of the signature of an expected noise source, it is possible to employ a simple energy detector to reject low SNR noise components,. It is also possible to build a clustering/tracking algorithm which might replace the human operator to identify a valid DOA measurement. We have yet to implement either of these.

Finally, the PBD operates within a significant DSP environment which, with further development, might be utilized for signature analysis and more sophisticated clustering of DOA estimates. These can be helpful in determining the nature of the collision threat and as aids in calculating avoidance solutions.

III. RECENT EXPERIMENTS

We indicated in the previous section that the PBD needs to be tuned to the dominant spectral components of an energy source for best performance. Unfortunately, we did not have the resources to evaluate the radiated spectra of platforms of opportunity prior to constructing a PBD. We also did not have access to a platform able to carry a PBD tuned for the lower spectral components that we anticipated would provide the best results. We therefore were limited to using a PBD built upon an existing modem infrastructure for a system designed to operate in a 9 – 14 kHz band. Two variations of this PBD were built and deployed. Figure 3 shows the first variation installed in a typical Teledyne Benthos glass housing. This assembly includes the PBD electronics and hydrophones, batteries, and a burn-wire release, and is integrally constructed as part of a standard Teledyne Benthos modem.

Figure 3. A 9 – 14 kHz PBD and modem housed in a 6000 m glass sphere plus a second unit in a 2000 m cylindrical housing.

This unit was deployed in Cape Cod Bay for approximately 4 hours to measure and record DOA from our own small boat. During the exercise, a tug boat hauling a very large structure emerged from Cape Cod Canal, which feeds into the Bay, and its radiated noise captured the PBD. We could not measure the radiated spectrum of this boat, and, again, we operated in the 9 – 14 kHz region. Figure 4 shows one snapshot of the encounter. The solid blue line is the AIS-reported track of the boat, while the red line is the bearing estimate made by the PBD. The range in this snapshot is approximately 0.75 km. Also shown is our own source which was positioned approximately 250 m from the PBD. It was not transmitting at this moment. A second snapshot is shown in Figure 5, where the boat has passed the PBD and is heading away. The boat was captured by the PBD at a range of approximately 1 km, and lost at a range of approximately 0.8 km.

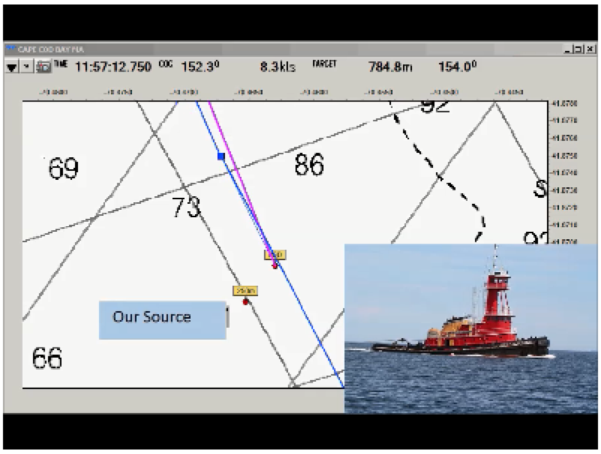

Figure 4. One snapshot of the PBD providing bearing to an approaching tugboat at a range of approximately 750 m.

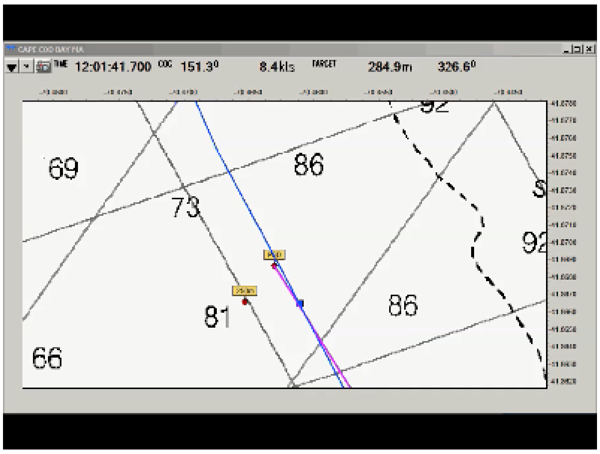

Figure 5. A second snapshot of the PBD providing bearing to a departing tugboat at a range of approximately 300 m.

The second experiment was conducted off of Kona Hawaii in a collaborative exercise with Liquid Robotics and Lockheed Martin. A variant of the Liquid Robotics Wave Glider was used for this experiment. Three gliders were configured to pull a tow body hosting a PBD, as shown in Figure 6. The 9 – 14 kHz PBD is the black cylinder midway down the length of the body and underneath. Figure 7 is a photograph of a subsea unit being towed by the glider

Figure 6. A Liquid Robotics tow body hosting a Teledyne Benthos PBD.

On one day of the testing, two Wave Gliders were positioned as shown by the red clusters in Figure 8. These clusters show the complete track of the gliders during the exercise. This snapshot shows the gliders at one position in their respective tracks. The blue line shows the complete track of a surface boat, while the two purple lines are the PBD bearing at this one instant. The maximum operating range for this experiment was approximately 1.5 km

We have emphasized the 9 – 14 kHz band of the PBDs used in this experiment simply because we had ready infrastructure for these experiments. The implications of this are illustrated by Figure 9, which shows three plots. The lower left hand plot shows the same boat spectra information as in Figure 1, but we have marked with a red line the 9 – 14 kHz region. The lower right hand plot shows the ambient noise spectrum when the boat was stopped (engines off). For the frequency range we had available, there is only approximately a +6 dB SNR opportunity. The upper plot simply shows a trace of received amplitude vs. time and shows the time at which the data for the lower two plots were obtained.

These plots clearly show that an increase in SNR of nearly 10 dB would have been available had we been tuned for a much lower frequency. We estimate that this likely would have more than doubled the range over which the PBD would have been able to maintain "track" on the target.

Figure 7. Undersea photograph of a Liquid Robotics Wave Glider (submarine portion) with a tow body.

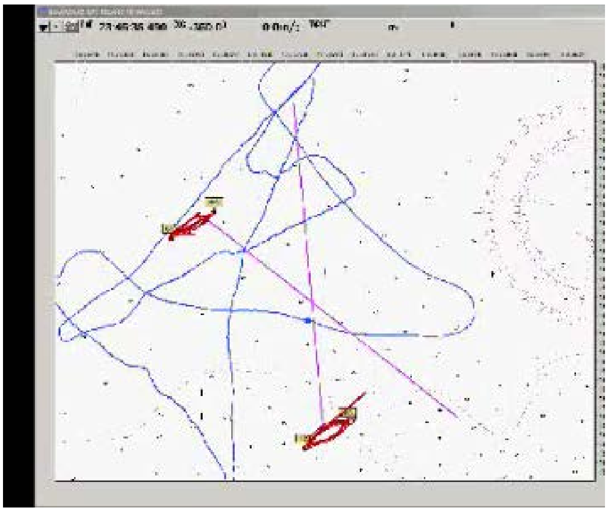

Figure 8. Snapshot of the Kona experiment, with two Liquid Robotics Wave Gliders each hosting a 9 – 14 kHz Teledyne Benthos PBD.

We are building and testing a variant of the PBD tuned for approximately 1600 to 3600 Hz. A drawing is shown in Figure 10. Although not nearly as compactly housed as done with the high frequency PBD, the algorithms required for this frequency require simple parameter changes. The lower frequency requires different bandpass filters, and rather more care must be exercised in handling. This design leads to a potential design for the Wave Glider, as shown in Figure 11. It is not yet clear if we will build this.

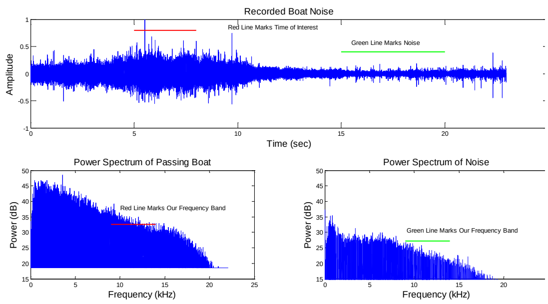

Figure 9. Temporal and spectral details of the boat radiation off of the Kona coast.

IV. CONCLUSIONS

The PBD is designed to estimate the DOA of any radiation of broadband acoustic energy, provided that energy has suitably strong components within the passband of the PBD. Experiments have shown excellent performance even with the operating band far removed from the optimal spectral component of the test platform. Experiments are planned for the near future to test its performance in isolated marine sanctuary areas, specifically to ascertain its value for detecting illegal fishing and other activities.

The DSP environment in which PBD algorithms are implemented offers considerable computational resources to enable upgraded signal detection and classification to aid the host platform to maneuver in a timely manner to avoid the possibility of collision.

Figure 10. An artist's rendering of a static, low frequency PBD

Figure 11. An artist's rendering of a potential low frequency PBD and Wave Glider integration.

V. ACKNOWLEDGEMENTS

We wish to thank Liquid Robotics for permission to include discussions, drawings and photographs related to the Wave Glider and tow body.