IMPROVING PROTECTION AGAINST INTRUDERS USING PASSIVE SONAR

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Abstract: *Divers and small vessels are increasingly recognized as a potential threat to high value assets. Harbour and waterside surveillance systems that are used to counter the threat of divers are usually based on active sonar, whose performance can be limited by reverberation in a harbour environment.*
Passive techniques are based on the detection of the sound emitted by the target. They are covert and yield information on the sound radiated by the detected source that can be used for classification. These advantages justify considering passive sonar as the basis for a waterside surveillance system, or as a supplement to a system based on active sonar.
Experimental results illustrating some capabilities of passive techniques, such as the detection and tracking of divers and surface vessels using a network of passive nodes, are presented. The experiment was performed in collaboration with the Stevens Institute of Technology (NJ, USA). Possible uses of these techniques in either purely passive systems or to augment active systems are discussed.
Keywords: *waterside security, intruder, diver, passive sonar*

1. INTRODUCTION

The bombing of the USS Cole in 2000 led to increased concern regarding the security of waterside infrastructures. Small vessels and divers are now seen as potential threats as they can be used to conduct terrorist or smuggling activities. This has triggered reaction from governmental agencies in the USA [1][2] and elsewhere, whose mandate includes waterside security. Waterside or port security systems are now available based on multiple sensor types ranging from cameras (visible and infra-red) and radars to sonars and ship automatic identification system (AIS); satellite imaging is also considered for wider area surveillance. The focus of this paper is on the detection of underwater intruders. Among the listed sensor types, only sonars are able to detect and track underwater targets. In the past, the preferred approach has been to use active sonars and several manufacturers now propose sonars that are dedicated to intruder detection [3].

The investigation of the passive approach was initiated in [4], where the observation of a broadband acoustic emission at the breathing rate of a scuba diver was reported. This fuelled further research on characterizing the acoustic emission of scuba apparatus [5] and on developing hardware and software solutions to detect it [6].

This paper reports on experiments on passive detection and localization of surface and underwater intruders. The principle of detection and localization and examples of experimental results are presented. These are followed by a discussion on the possible use of the presented approach for waterside security.

2. PRINCIPLE OF DETECTION AND LOCALIZATION

The proposed approach for passive detection and localization of underwater and surface threats is based on the use of a network of passive sonars. The function of a passive sonar is to detect and characterize sound sources and return their direction. Each passive sonar communicates its detections to a fusion unit that combines the detections from the various passive sonars into target positions and tracks. The detection of the source by a passive sonar and the localization by the fusion unit are presented in this section.

Unlike active sonars that emit acoustic energy, passive sonars detect targets by the sound radiated by the target. An active sonar can evaluate the target range by measuring the time between the emission of a ping and the reception of an echo from the target. Passive sonars cannot measure the travel time because the time of emission of a signal from a target is usually unknown. They can, however, be used to measure the time difference of arrival (TDOA) between different passive elements, which enables localization in the near field [7] but yields only the direction for targets in the far field [6].

The detection of acoustic sources is performed by means of TDOA measurements between the various hydrophones composing the passive sonar system. The approach has been presented in [6] and uses the generalized cross-correlation (GCC) [8]. The generalized cross-correlation $R\psi(\tau)$ between signals $x_1(t)$ and $x_2(t)$ is defined as:

$$R\psi(\tau) = \int_{-\infty}^{\infty} \psi(\omega) X_1(\omega) X_2^*(\omega) e^{j\omega\tau} d\omega \tag{1}$$

where $X_i(\omega)$ is the Fourier transform of $x_i(t)$, * denotes complex conjugation and $\psi(\omega)$ is a frequency weighting function. With $\psi(\omega)=1$, the GCC reduces to the conventional cross-correlation. A particular case uses $\psi_{PHAT}(\omega)=1/(|X_1(\omega)||X_2(\omega)|)$, which can be interpreted as a whitening of the cross-spectrum. It is called phase transform (PHAT) because it only uses the phase information of the signal spectrum. When the frequencies which are amplified contain a signal (broadband source), the peak in the phase transform becomes sharper than with the conventional cross-correlation, but if the frequencies that are amplified only contain noise, the performance of this method decreases. Various alternate GCC methods have been proposed in the literature to mitigate this issue.

The phase transform has been retained as a good candidate for the detection of the scuba acoustic emission because of its broadband character. Acoustic sources are detected in the phase transform by finding the peaks exceeding a preset detection threshold. The delay τ_0 of the cross-correlation peak is related to the direction of the source θ_0 with respect to the hydrophone pair according to $\tau_0=\tau_{\max}\cos(\theta_0)$, where the direction is measured from endfire (i.e. $\theta_0=0$ corresponds to a source in line with the hydrophones) and $\tau_{\max}=d/c$ is the maximum possible TDOA between the two hydrophones separated by distance d in a propagation medium with speed of sound c. The locations that correspond to a same delay form a hyperbola in 2D (hyperboloid in 3D). The relationship between delay and direction is a far field simplification corresponding to the asymptotes of the hyperbola: it corresponds to the assumptions that the target range is much larger than both the sonar baseline (far field) and the water depth (2D).

Because the cosine function is even, there are two bearings corresponding to a same measured delay: $\theta_0^{\pm}=\pm\arccos(\tau_0/\tau_{\max})$, among which one is the true target direction, the other is referred to as ghost. For some deployment configurations, such as mounted on a pier, the water is only on one side of the hydrophone pair, so that only one of the two possible directions can physically correspond to an underwater target (no underwater target on the land side). If this is not the case, at least one additional non-collinear hydrophone is required to solve the ambiguity in direction. With three hydrophones, three pairs can be formed. The phase transform is computed for each pair, the delays of the peaks are extracted and converted into pairs of true-ghost directions. The true direction corresponds to the direction of the source and is the same for each pair, whereas the direction of the ghosts is pair dependent. This property is used to identify the true direction and discard the ghosts.

Knowledge of the frequency content of the detected sound sources is useful for classification and association of detections from several passive sonars. Some frequency information can be extracted as a function of the direction by applying a GCC over frequency sub-bands. The frequency range can be partitioned into N frequency bands using non-overlapping binary masks $M_k(\omega)$ so that $M_k(\omega)=$ 0 or 1 and $\sum_{k=1}^{N} M_k(\omega)=1$. These masks are used to define $R_k(\tau)$, the GGC with weighting function $\psi_k(\omega)=M_k(\omega)\psi_{PHAT}(\omega)$. These GCC satisfy $\sum_{k=1}^{N} R_k(\tau)=R_{PHAT}(\tau)$, which means that the phase transform is the superposition of the contributions from the various frequency bands. $R_k(\tau_0)$ is the contribution of the frequency band corresponding to $M_k(\omega)$ in the peak at $\tau=\tau_0$ in the phase transform. It provides information on the frequency content of the source at delay τ_0, and can be used to evaluate which source dominates in which frequency band.

The processing of the signals from each passive sonar results in a stream of detections containing detection time, estimated direction and information on the frequency content. These detections have to be further processed to localize, classify and track the targets. In the case of a single detection from two separate sonars, the target location can be found by intersecting rays starting from the passive sonars and going in the direction of the detected source. In the presence of multiple sources and false alarms, there can be many rays initiated from each sonar, thus leading to a number of ray intersections that exceeds the number of targets. The detections of a same target from the various sonars have to be properly associated to estimate the correct target location. Because the presence of other targets, such as for example boats, is likely during an intrusion, the localization procedure has to accommodate with this complexity. A probability hypothesis density (PHD) particle filter [9][10] has been considered to solve the localization problem, the presentation of which exceeds the scope of this paper.

3. EXPERIMENTAL RESULTS

This section presents examples of experimental results obtained by applying the described approach to datasets collected during a trial organized jointly between TNO and the Stevens Institute of Technology (NJ, USA) in October 2010 in the Royal Netherlands Navy harbour of Den Helder. Initial results from this trial have been presented in [11]. The trial involved SPADES [6], the system developed by the Stevens Institute of Technology and an acquisition system from SMID Technology S.r.l., Italy. Both systems are equipped with 4 hydrophones, sampled at 200 kHz for SPADES and 192 kHz for the SMID system. SPADES hydrophones were deployed on stands placed about 60 cm from the bottom, with a total baseline of about 70 m. The hydrophones of SMID were deployed as a linear array at the end of a pier with a baseline of 180 cm. Acquisition of acoustic signals was performed as divers or boats were approaching or passing by the deployed sensors. The divers involved in the trial were towing a surface float that was equipped with a GPS tracker. The GPS track can be used to estimate the diver range and direction to the sensor as a function of time, and can be used to validate the acoustic detection.

Figs. 1 and 2 present examples of recorded signals and correlation computed using the phase transform. The top plot shows the spectrogram, which represents the frequency content as a function of time. The second plot represents the correlation as function of time. The vertical axis represents the delay, which corresponds to the target direction. We will refer to such a plot as a *correlogram*, although the term correlogram is often used to refer to the plot of a single cross-correlation. Several observations can be made on the spectrogram in Fig. 1. The low frequency content (up to 20 kHz) is dominated by shipping and environmental noises that have a rather continuous character. An active acoustic system is present at 50 kHz, and noise is present over 70 kHz. The latter is due to the analog to digital converter used in the SMID acquisition system. This system was developed for measurement below 60 kHz in a different context, and was used here only on loan. Different technological choices would have been made if the required bandwidth had been larger. For this reason, the frequency content over 70 kHz has not been used in the processing.

Finally, some vertical stripes corresponding to an intermitted broadband emission are visible: these correspond to the diver signal. It is possible to associate events in the spectrogram with their direction in the correlogram because both plots share the same temporal axis. The correlogram presents some rather continuous lines, which correspond to boats and a dashed line, corresponding to the diver who is detected at each broadband emission.

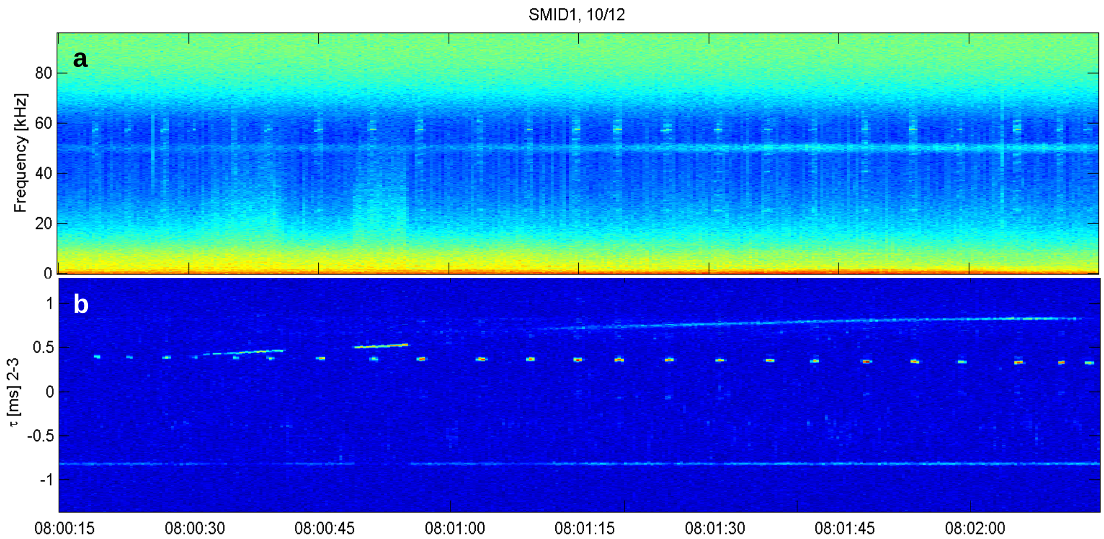

Fig.1: Spectrogram (a) and correlogram (b) showing a boat and a diver (at 190 m)

Fig. 2a presents an example of the phase transform computed by frequency band. Three targets are present. The target (α) is a boat that dominates the low frequency content. Target (χ) is another boat with dominant spectral components around 20 kHz and 50 kHz (this boat is the owner of the 50 kHz active system). The spectral components of target (β) are predominantly around 35 kHz and 60 kHz. It is one of the divers. This figure illustrates the possibility of extracting information that is a function of both frequency and direction using the GCC. This information can be used to characterize the frequency content of the sources detected in various directions. In Fig. 2b, the peaks that were automatically detected are plotted as a function of time for about 20 min of recorded data. Each of the detections is represented by a dot whose colour has been chosen based on the ratio between high and low frequency content. Low frequency contacts are shown in red and high frequency contacts in green: the diver tracks appear in green whereas the large majority of other detected events appear in red.

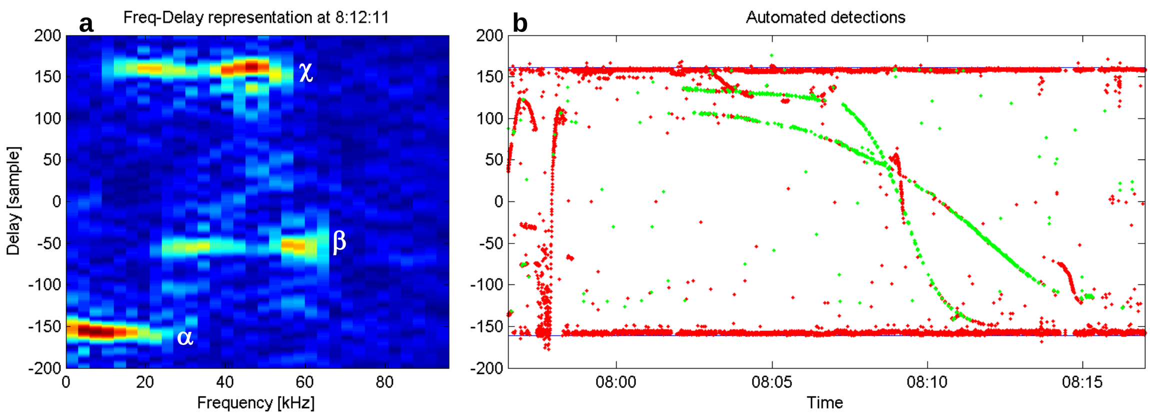

Fig.2: (a) Example GCC for various frequency bands. (b) Example of automated detection in GCC. The colour was chosen based on the ratio between HF and LF content estimated using frequency dependent GCC. Most green dots correspond to diver detections, most red dots correspond to boat detections.

Fig. 3 presents two examples of localization results obtained by processing the contacts from the passive sonars with the PHD particle filter. The sensor positions (centre of hydrophone pairs) are represented with black squares. The localized targets are represented with ellipses placed at the location of the detection and whose size represents the localization uncertainty. The colour indicates the time at which the detections occurred, going from blue for the earliest events to red for the most recent events. In this representation, the track of a target exhibits a rainbow pattern, whereas false detections would results in random coloured spots. Fig. 3a is an example of localization of a boat using 3 pairs of hydrophones from SPADES. Fig. 3b shows the tracks of two divers obtained by fusing the data from two pairs of hydrophones from SPADES and one pair of hydrophones from the SMID system. The tracks of the two divers are resolved: this demonstrates the feasibility of the approach using passive sonars that do not share the same time base, i.e. localization at a data fusion stage.

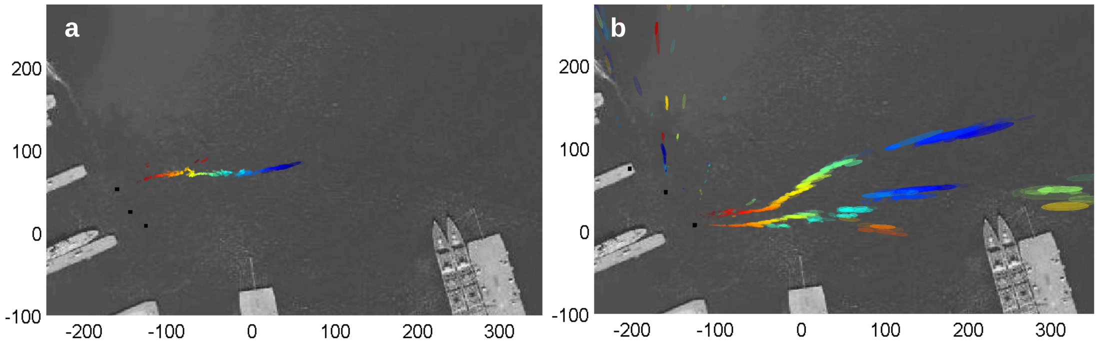

Fig.3: Automated boat (a) and diver (b) localization with PHD particle filter.

4. DISCUSSION AND POSSIBLE APPLICATIONS

The presented results demonstrate the possibility of passively detecting, classifying and localizing scuba divers at range up to 300-350 m in an operational harbour. This indicates that passive sonar presents a real potential for underwater intruder detection. It is also sensitive to other types of targets relevant to waterside security, such as boats. Additional advantages of passive sonars include covertness and absence of disturbance of marine life (e.g. mammals). These capabilities can be used to develop various systems relevant to maritime/harbour security, including in environmentally protected marine areas.

A network of passive sonar can be deployed in and around an area to protect, providing localization of surface vessels and divers. Less ambitious deployments can involve for instance two passive sonars deployed on either side of the entrance of a harbour to monitor incoming and outgoing traffic. This bears similarity with the trip-wire idea proposed in [12], but would present the advantage of not requiring an underwater cable running across the harbour entrance, which could be damaged in case of dredging, mooring or fishing in the area. This is important from an operational point of view, since a security system should ensure protection functions without hindering the usual activity of the protected area. Other purely passive applications can be envisioned. For instance security and anti-terrorist booms, which are reinforced lines of floats used to physically prevent the access to some water area by surface vessels, can be instrumented to provide awareness about the underwater situation. An even simpler device composed of a single sonar and devoid of localization capability could be used for area clearance, for instance to ensure the absence of a diver prior to entering the water.

Regarding the problem of waterside security in a wider sense, passive acoustic technology can be added to existing security solutions to improve the underwater situation awareness. This is true for security solutions involving active sonar as well. Passive sonars are not sensitive to the same characteristics of the target as active sonars, therefore offering an independent view on the underwater situation. Passive and active systems can be combined in various ways. Passive sonars can be used to increase the coverage area and to provide early warning capabilities, possibly at a lower cost than using additional active sonars especially in reverberation limited environments. Passive systems can also be used in direct conjunction with a collocated active sonar: the detections of the active sonar can be augmented with classification clues from the passive sonar if the latter performed a simultaneous detection of the target.

5. CONCLUSION

The experimental results presented in this paper demonstrate the feasibility of passive detection of scuba divers up to distances of the order of 300-350 m in an operational harbour environment. This distance corresponds to the maximum distance at which the diver entered in the water. This detection range enables a sufficient response time to consider using passive sonars for the underwater layer of waterside security systems. Various applications have been proposed that involve either passive or hybrid active-passive solutions.

The authors believe that the development of passive sonars for waterside security applications into operational devices will be mainly constrained by two aspects. On one hand, future regulation may limit or even forbid the use of active sonars in some areas to prevent adverse effects on the marine life. The underwater protection of such areas would have to be performed with passive solutions, possibly activating active sonars only in case of a detected threat or a high alert level. Implementation of such regulation will create a demand for a passive sonar solution. The other aspect is related to the detection capabilities of passive sonars. If scuba divers are considered as a likely underwater threat, other types of target constitute potential underwater threats, such as divers equipped with propulsion vehicles, unnamed underwater vehicles and divers equipped with rebreathers. A robust security solution should detect and localize any relevant type of threat. Among these, rebreathers are the most problematic. Rebreathers are breathing devices that recycle the air exhaled by the diver. They produce few or no bubbles at the surface and generate much less noise than scuba. Consistent detection of rebreathers with passive acoustics has not been reported yet. Positive results in that direction are required to develop efficient purely passive underwater security systems. Otherwise, rebreather detection will require the use of an active sonar. Nevertheless, even in such a case passive sonar can be used for the advantages it provides in terms of classification clues.

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