Passive Detection of Scooter's Underwater Radiated Noise

Roee Diamant[1],[2], Fausto Ferreira[2],[3]
[1]University of Haifa, Department of Marine Technology, Haifa, 3498838, Israel, roee.d@univ.haifa.ac.il
[2]University of Zagreb Faculty of Electrical Engineering and Computing,
Laboratory for Underwater Systems and Technologies, 10000 Zagreb, Croatia
[3]CoE MARBLE - Centre of Excellence in Maritime Robotics and Technologies
for Sustainable Blue Economy, 10000 Zagreb, Croatia

***Abstract*—Acoustic detection of submerged vessels or submarines by small low-cost devices arranged in an internet of underwater things (IoUT) offers distributed sensing with easy deployment from moorings, vessels or air. In this paper, we propose a probabilistic approach to detect the underwater radiated noise (URN) of submerged scooters. Our method builds upon expected distortions in the radiated noise of the scooter that leads to a complex harmonic pattern. A stability test for harmonics then verifies detection. Results from two sea experiments with two different scooters show favorable tradeoff between the false alarm rate and the detection rate that improves as the vehicle's speed increases.**

***Index Terms*—Underwater radiated noise, submerged Scooter, Clustering, Harmonic detection**

I. Introduction

Acoustic detection of electric unmanned underwater vehicles (UUVs) or Diver Propulsion Vehicles (DPVs) is a challenging task due to the weak acoustic signature of the acoustic radiated noise. The underwater radiated noise (URN) from such vessels may include high power impulsive transients generated during ignition [1] as well as cavitation noise caused by the collapse of vapor bubbles near the propeller. Methods for distinguishing between vessel's and ambient noise assume that the ambient noise is diffuse, while its anthropogenic component is directional and can therefore be extracted by array processing [2]–[4]. In this paper, we target the security field of threat detection. In particular, we focus on the defense of critical marine infrastructures such as oil & gas rigs and underwater cables by detecting divers with DPVs, commonly known as scooters.

Scooters are typically used by divers as a way of extending their operations range and speed and reducing fatigue. There are scooters for different applications including recreational, scientific and military. Scooters are propelled by electric thrusters and are controlled and maneuvered by a scuba diver that uses the scooter as a mean to travel fast with minimum effort. A picture of a diver holding a scooter from our sea experiment is shown in Figure 1. For a recent review on DPVs/scooters, we refer to [5].

This work was funded in part by the NATO Science for Peace and Security Programme under grant id. G7646 (SHIELD), and by the European Union's Horizon Europe programme under grant no. 101086340 (UWIN-LABUST)

As scooter are small devices and are often used by divers close to the sea boundaries, they are difficult to detect by active sonar, e.g., transmitting prob acoustic signals and analyzing the received reflections. This is because, near the surface, the signal to clutter ratio of the reflection pattern is extremely weak [6]. Alternatively, passive acoustic detection holds the potential to recognize the noise emitted by the scooters. In particular, to identify stable periodic components in the signal in the form of narrowband tonal lines, which is different than the Gaussian-like distribution of the ambient noise. By our measurements, these narrowband components in the signal also include a complex harmonic pattern due to misalignment in the scooter's thruster. Tailored to these observations, our solution for passive detection of scooter's radiated noise includes cyclostationary analysis for harmonic detection followed by a stability test. To the best of our knowledge, while scooters are fast adopted by scuba divers due to their ease of operation and low cost, this is the first specific solution to detect the noise radiated by these vehicles.

A. Related work

The literature is rich regarding the passive detection of ships URN. Typical approaches use use power spectrum analysis methods over the DEMON representation of the received signal [7], [8]. Other methods combine cyclostationary analysis and principal components analysis [9], or search for stability in the noise pattern [10]. An overview of tracking approaches for URN detection and ways to analyze the narrowband noise components to characterize ships is provided in [11]. A few approaches present an infrastructure and/or algorithms that detects both DPVs, UUVs and ships but do not specifically address DPVs. For instance, in [12], a combination of active and passive sonar is suggested in the framework of an underwater sensor network. Likewise, the Stevens Passive Acoustic System for underwater surveillance [13] included 4 hydrophones statically deployed to detect UUVs, DPVs, swimmers and divers. This system applies cross-correlation for a delayed version of the signal with an operator manually choosing the frequency band of interest.

One of the main issues with the detection of small UUVs or DPVs is that they are much quieter than ships and thus harder

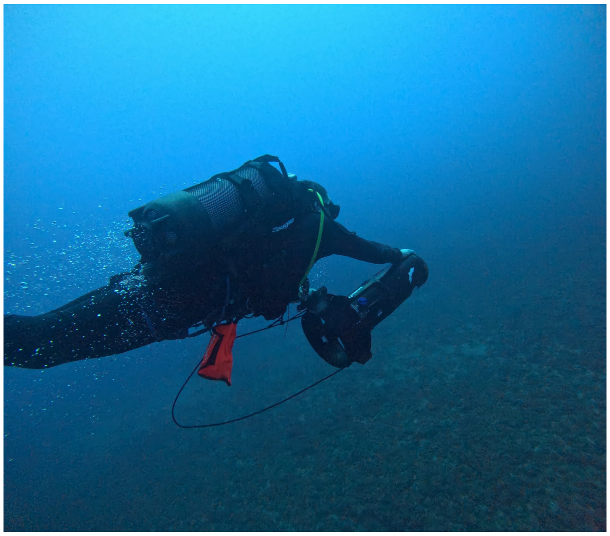


Fig. 1. Picture from the data collection of a scuba diver and a scooter.

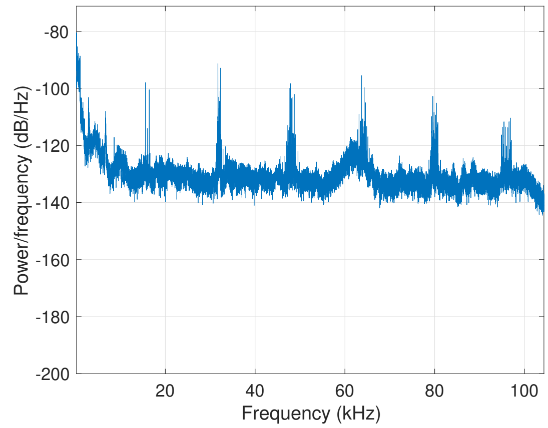
to listen/detect. An acoustic scattering characterization provided by [14] investigates the stealth capabilities of DPVs. Due to this aspect, some authors perform active detection [15], [16] and others use arrays [3], [4], [17] or utilize vector sensors [18] as means for directional reception when performing passive detection. To get directionality, the work described in [17] uses a tetrahedral array. The work in [19] uses two hydrophones and for detection of Remotely Operated Vehicle (ROV) using simultaneous particle image velocimetry (PIV) measurements to identify the components of the overall observed spectrum. An hybrid system in [20] combines both passive and active sonar is used to first passively detect an UUV by finding periodic patterns in the cross-correlation output of an hydrophone array, followed by vehicle's localization and tracking using an active sonar. However, no solution is offered for the detection of DPVs or UUVs using the realistic setup of a single hydrophone system.

The remainder of the paper is organized as follows. Section II presents our detection methodology. Section III shows results based on recordings from sea trials. Finally, Section IV concludes the paper.

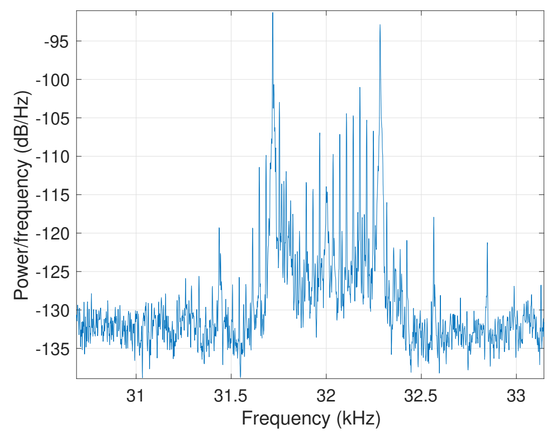
II. Methodology

A. Data collection

To characterize the noise of the scooter, we have performed a data collection experiment. The experiment included an OceanSonic IcListen acoustic recording unit (256 kHz sampling frequency at 3B per sample) attached to a scuba diver that used a Secraft GO! scooter. We tested two scooters of the same type, each at a different diving session. The two tests took place at Dec. 2024 in Eilat, the Red Sea at a depth of 20 m. The divers operated the scooters continuously at three speed values: 0.5 knot, 1 knot and 2 knots. An underwater camera was pointed to the scooter's screen showing the current speed for offline analysis. For false alarm estimation, the recorder was placed in the water for ambient noise recording



(a) Full spectrum.



(b) zoom-in.

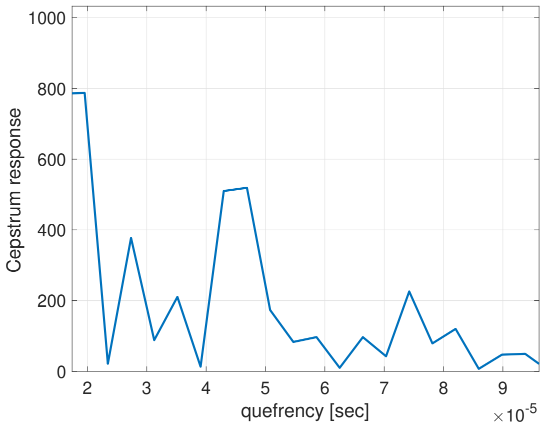
Fig. 2. Spectrum of the recorded scooter's noise. Speed 1 knot.

for two hours between the two diving sessions. A picture from this experiment is shown in Fig. 1.

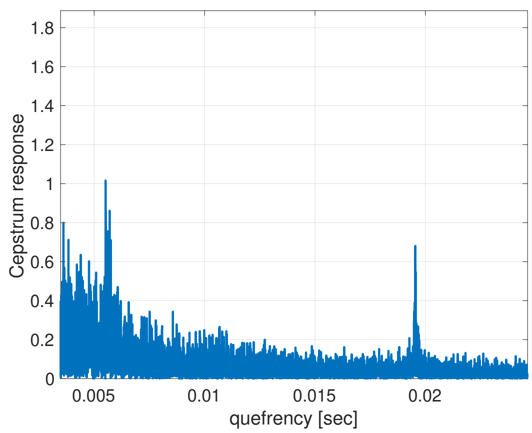
Data was collected during two 40 min dives. As preprocessing, the noise from the divers' breathing system was identified and removed from the data. This was done by an energy detector tuned to a wideband signal from DC to 100 kHz, assuming the scooter noise is narrowband. A second pre-processing included identifying the scooter's operation times by manually observing the diver's camera video footage. This yielded acoustic segments arranged by the scooter's speed.

B. Characterization of Scooter Noise

A spectrum of the scooter's recorded noise for speed of 1 knot is given in Fig. 2. We observe a set of narrowband signals with harmonics starting at 15.6 kHz with a maximum of 10 dB reduction until 97 kHz. The similarities between the intensity of the fundamental frequency and the harmonics may reflect a defect in the rotating system. Signal-to-noise ratio is above 20 dB, but we recall that this level is received when the recorder is attached to the diver, roughly 1 m from the scooter's thruster. We report that this noise is continuous with



(a) Cepstrum of entire signal.



(b) Cepstrum of band 31 kHz to 34 kHz.

Fig. 3. Cepstrum response for the signal's spectrum in Fig. 2a.

almost no intensity reduction. As expected, the basic harmonic frequency changes with the scooter's speed. The high carrier frequency makes the noise negligible to the diver's ear, but well observed by a recorder with a high sampling frequency.

A zoom-in for the first harmonic is given in Fig. 2b. We observe a complex structure of narrowband signals that reflect the scooter's thruster acoustic signature. Together with the observable harmonics, this structure may serve as a characteristic feature for the detector.

C. Detector Design

Our detection pipeline includes three steps: 1) cyclostationary analysis to find harmonies in the signal, 2) a search for harmonic stability by comparing the detected harmonies over time, and 3) detection verification by identifying multipeaks in each harmonic band.

1) Harmony Detection: Expecting a low SNR for the received signal, the harmonics in the signal may be hard to detect directly by e.g., spectrum analysis. Instead, relying on the harmony consistent spacing in the spectral domain, we perform harmony identification in the cepstral domain. Cepstrum analysis is the inverse Fourier transform of the logarithm of the signal spectrum. The fundamental frequency in the cepstral domain would correspond to the inverse of the harmonic frequency difference. The cepstrum response for the signal's spectrum in Fig. 2a is shown in Fig. 3a. Several peaks are observed, which reflects on the complex spectrum of the signal. To identify possible harmonies in the buffer, we match between cepstrum peaks and peaks identified in the power spectral density (PSD) of the signal.

Denote $\mathbf{f} = f_1, \ldots, f_N$ as the series of frequencies found as dominant peaks in the PSD above a certain carrier frequency $f_{\min}$. Also denote $\mathbf{c} = c_1, \ldots, c_M$ as the series of quefrency found as dominant peaks in the cepstral analysis. A harmonic association $\mathbf{h}(c_i)$, $c_i \in \mathbf{c}$ would include pairs (f_n, f_m), $f_n, f_m \in \mathbf{f}$ for which $c_i - \delta < |f_n - f_m| < c_i + \delta$ and δ is a parameter set by the sampling frequency to compensate on the PSD quantization error. To obtain c_i and, by which the harmonic association, we solve the following optimization problem

$$\mathbf{h} = \underset{c_i}{\operatorname{argmax}} \, ||\mathbf{h}(c_i)||, \tag{1a}$$

$$\text{s.t. } c_i - \delta < |f_n - f_m| < c_i + \delta, \quad \forall (f_n, f_m) \in \mathbf{h}(c_i) \tag{1b}$$

$$(f_n, f_m) \perp (f_k, f_l), \; (f_n, f_m), (f_k, f_l) \in \mathbf{h}(c_i) \; , \tag{1c}$$

to search for the largest set of harmonic assignment, where $|| \cdot ||$ stems for the rank of a set.

2) Testing Harmonic Stability: The second processing step search for stability among all harmonic components identified by the cepstrum analysis. To this end, we divide the received signal into short time buffers of T s and, in each, find the dominant harmonic components. Stability is tested over the identified harmonies. This is performed as a clustering problem to find classes of condensed values. Using a clustering solution allows a flexibility degree and eliminates outliers.

Consider a division into N buffers. Let set $\mathbf{H}$ includes the individual frequencies in the obtained sets $\mathbf{h}$ in all time buffers, where $L = ||\mathbf{H}||$. Determine K, the maximum number of clusters, as the number of identified frequencies in the largest set $\mathbf{h}$. Let $\mathbf{s}_k$ be a binary vector of degree L for which a '1' in element i indicates that the ith frequency is included in cluster k. We model the *stability* of the whole ensemble of K clusters as:

$$\sum_{k=1}^{K} \mathbf{s}_k^{\mathrm{T}} \mathbf{W} \mathbf{s}_k - \sum_{k=1}^{K} \mathbf{s}_k^{\mathrm{T}} \mathbf{D} \mathbf{s}_k \; , \tag{2}$$

where $\mathbf{D}$ is a diagonal matrix whose (i, i) entry $d_{i,i}$ is the sum of similarities of the ith frequency to all other identified frequencies,

$$d_{i,i} = \sum_{j=1}^{N} w_{i,j} \; , \tag{3}$$

where $w_{i,j}$ is the Euclidean distance between frequencies i and j arranged in matrix $\mathbf{W}$. In (2), the first term quantifies distances within the cluster while the second term reduces the probability to obtain large clusters. We choose this formalization to direct the solution to form high rank clusters only for true assigned harmonies.

The solution for the clustering problem is found by solving the optimization problem

$$\begin{aligned} \underset{\mathbf{s}_k}{\operatorname{argmax}} & \sum_{k=1}^{K} \mathbf{s}_k^{\mathrm{T}} \left(\mathbf{W} - \mathbf{D}\right) \mathbf{s}_k, \\ & \text{s.t. } \mathbf{s}_k \perp \mathbf{s}_l, \forall k \neq l \,. \end{aligned} \tag{4}$$

The problem in (4) is the same form as the minimal cut problem [21]. For matrix $\mathbf{S}$ containing vectors $\mathbf{s}_k$ as columns, the problem can be effectively solved by

$$\begin{aligned} \underset{\mathbf{C} \in \{0,1\}^{N \times K}}{\operatorname{argmin}} & \quad \mathrm{Tr}(\mathbf{C}^{\mathrm{T}}\mathbf{D} - \mathbf{W}\mathbf{C}), \\ & \text{s.t. } \mathbf{C}^{\mathrm{T}}\mathbf{C} = \mathbf{I} \,, \end{aligned} \tag{5}$$

where $\mathrm{Tr}(\cdot)$ is the matrix trace and $\mathbf{I}$ is the unity matrix.

3) Detection Verification: The final step in our detection scheme is a search for a complex harmonic response. Such a pattern is evident in Fig. 3b. This is performed by determining is a sufficient number of stable harmonies have been detected. Let ρ_k be the number of frequencies in a cluster k, such that

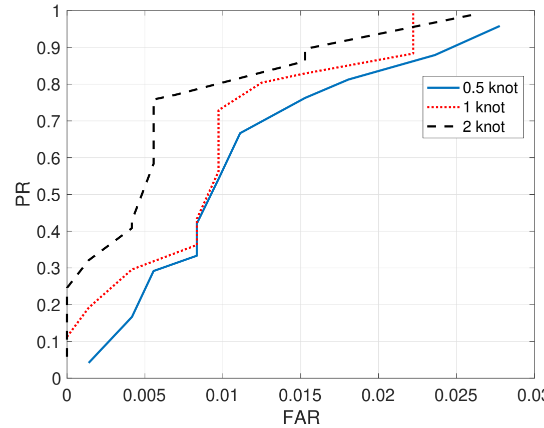
$$\rho_k = \sum_{k=1}^{K} \mathbf{s}_k \,.$$

The harmonic detection is determined valid if there is at least $K/2$ clusters for which $\rho_k > \mathrm{Th}$. Note that the stability threshold, Th, is the only threshold in our scheme. Arguably, this contributes to the robustness of the detector as scooters may produce various harmonic patterns.

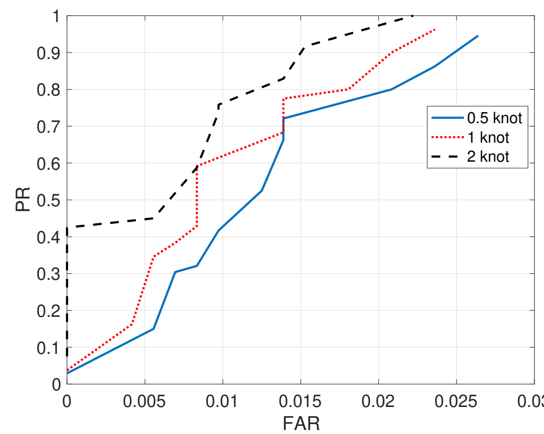
III. Results

Our results were obtained separately for the two recorded scooters recorded. For analysis, we considered time windows of 10 s during which the speed of the scooter was expected to be stable. Each time window was divided into $T = 1$ s long buffers for stability testing. The detection was performed separately for each time window, such that for each dive of 40 min the number of detection attempts with scooter's noise was 240. To test a more realistic scenario, ambient noise recorded before the operation of the scooter was synthetically added to the signal acquired from the recorder mounted on the diver's tank to yield an SNR of 20 dB. False alarm calculation was performed for the 2 hour noise collection period in similar time windows to yield 720 detection attempts with no scooter's noise present. The minimum considered frequency for the detection was $f_{\min} = 10$ kHz. The stability threshold Th was used as a parameter to obtain the receiver operating characteristics (ROC). That is, for a choice of Th we receive a pair of detection rate (DR) and false alarm rate (FAR).

The ROC for the three speed values tested during the recording trials are presented in Fig. 4a and in Fig. 4a for scooter A and scooter B, respectively, and recall the SNR was set for 20 dB. We observe an improvement in detection as the speed increases. For example, for Scooter A and a speed



(a) Scooter A.



(b) Scooter B.

Fig. 4. ROC curves for different scooter speed as recorded during the experiment. SNR=20 dB.

of 1 m/s a FAR of 10^{-2} was obtained for a DR of roughly 72%, while for the same scooter at a speed of 2 m/s a similar FAR is obtained for a DR of 80%. This is because of increased harmonics resulting from instabilities of the scooter's thrusters that increases with the speed. Comparing the results for the two scooters, no significant differences are observed in the ROC. Arguably, this demonstrates the robustness of our detector.

Next, we explore the ROC performance for different SNR values for a scooter's speed of 1 m/s. Average results for the two scooters are presented in Fig. 5. We observe stable detection performance up to an SNR of 5 dB. Considering the initial SNR of 30 dB as recorded on the diver carrying the scooter (see Fig. 2a), a decrease of 25 dB in the SNR would translate to detection from a distance of more than 100 m.

IV. Conclusion

In this paper, we derived a detection scheme aimed to identify the radiated noise of a submerged scooter. The method assumes a stable harmonic pattern in the radiated signal and includes a series of harmony detection, stability testing and

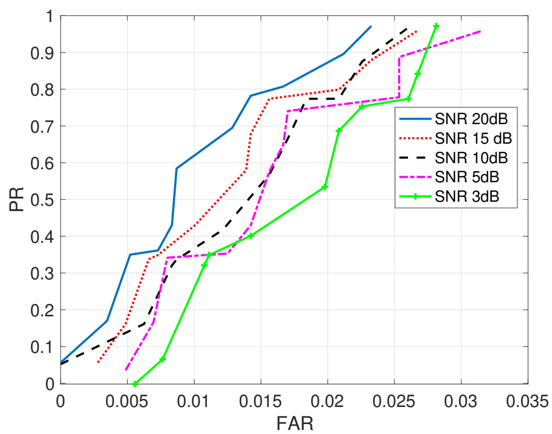


Fig. 5. ROC performance as a function of SNR.

search for a complex spectral pattern for detection verification. Results from recordings of two scooters demonstrated robustness in the detection in terms of the scooter's speed and up to an SNR of 5 dB, an similar performance when tested on two different scooters but of the same make. Future work will explore the effect of different scooter types, various environmental conditions as well as realtime detection test.

REFERENCES

[1] F. Jensen, L. Bejder, M. Wahlberg, N. A. de Soto, M. Johnson, and P. Madsen, "Vessel noise effects on delphinid communication," *Marine Ecology Progress Series*, vol. 395, pp. 161–175, 12 2009.

[2] C. Zhu, S. G. Seri, H. Mohebbi-Kalkhoran, and P. Ratilal, "Long-range automatic detection, acoustic signature characterization and bearing-time estimation of multiple ships with coherent hydrophone array," *Remote Sensing*, vol. 12, p. 3731, 11 2020.

[3] D. Nie, Z. Sun, G. Qiao, S. Liu, and Y. Yin, "Kite-type passive acoustic detection system for underwater small targets," in *2014 Oceans - St. John's*. IEEE, 9 2014, pp. 1–5.

[4] K. R. Kita, S. Randeni, D. DiBiaso, and H. Schmidt, "Passive acoustic tracking of an unmanned underwater vehicle using bearing-doppler-speed measurements," *The Journal of the Acoustical Society of America*, vol. 151, pp. 1311–1324, 2 2022.

[5] H. Qin, Z. Li, S. Xu, X. Liu, and X. Cao, "Review of diver propulsion vehicle: A review," *Physics of Fluids*, vol. 36, 10 2024.

[6] R. Diamant, D. Kipnis, E. Bigal, A. Scheinin, D. Tchernov, and A. Pinchasi, "An active acoustic track-before-detect approach for finding underwater mobile targets," *IEEE Journal of Selected Topics in Signal Processing*, vol. 13, no. 1, pp. 104–119, 2019.

[7] Q. Xie, C. Chi, S. Jin, G. Wang, Y. Li, and H. Huang, "Underwater tone detection with robust coherently-averaged power processor," *Journal of Marine Science and Engineering*, vol. 10, p. 1505, 10 2022.

[8] W. Guo, S. Piao, J. Guo, Y. Lei, and K. Iqbal, "Passive detection of ship-radiated acoustic signal using coherent integration of cross-power spectrum with doppler and time delay compensations," *Sensors*, vol. 20, p. 1767, 3 2020.

[9] Y. Song, J. Liu, L. Cao, N. Chu, and D. Wu, "Robust passive underwater acoustic detection method for propeller," *Applied Acoustics*, vol. 148, pp. 151–161, 5 2019.

[10] T. Alexandri and R. Diamant, "Detection and characterization of ship underwater radiated narrowband noise," *Computer Networks*, vol. 248, p. 110480, 2024.

[11] A. Pollara, A. Sutin, and H. Salloum, "Passive acoustic methods of small boat detection, tracking and classification," in *2017 IEEE International Symposium on Technologies for Homeland Security (HST)*. IEEE, 4 2017, pp. 1–6.

[12] N. Masaki, S. Hiroshi, M. Jun, M. Kenji, K. Minoru, and Y. Masahiro, "Special issue on solving social issues through business activities establish a safe and secure society underwater surveillance system to counteract associated underwater threats," *NEC Technical Journal*, vol. 8, 9 2013. [Online]. Available: https://www.nec.com/en/global/techrep/journal/recommend_year/2013/10.html

[13] A. Sutin, B. Bunin, A. Sedunov, N. Sedunov, L. Fillinger, M. Tsionskiy, and M. Bruno, "Stevens passive acoustic system for underwater surveillance," in *2010 International WaterSide Security Conference*. IEEE, 11 2010, pp. 1–6.

[14] J. Li, J. Fan, and B. Li, "Acoustic scattering characteristics of a diver propulsion vehicle," *Journal of Unmanned Undersea Systems*, vol. 30, pp. 733–739, 12 2022.

[15] B. Lei, Z. He, Y. Yang, C. Sun, and C. He, "Experimental demonstration of forward scattering barrier for auv intruder," *Applied Acoustics*, vol. 190, p. 108635, 3 2022.

[16] T. C. Yang, "Acoustic dopplergram for intruder defense," in *OCEANS 2007*. IEEE, 2007, pp. 1–5.

[17] K. E. Railey, "Demonstration of passive acoustic detection and tracking of unmanned underwater vehicles," Ph.D. dissertation, 2018.

[18] D. S. Terracciano, R. Costanzi, V. Manzari, M. Stifani, and A. Caiti, "Passive bearing estimation using a 2-d acoustic vector sensor mounted on a hybrid autonomous underwater vehicle," *IEEE Journal of Oceanic Engineering*, vol. 47, pp. 799–814, 7 2022.

[19] M. Cai and B. Bingham, "Passive acoustic detection of a small remotely operated vehicle," in *OCEANS 2011 IEEE - Spain*. IEEE, 6 2011, pp. 1–7.

[20] G. Sumithra, N. Ajay, N. Neeraja, and K. Adityaraj, "Hybrid acoustic system for underwater target detection and tracking," *International Journal of Applied and Computational Mathematics*, vol. 9, p. 149, 12 2023.

[21] U. Von Luxburg, "A tutorial on spectral clustering," *Statistics and computing*, vol. 17, no. 4, pp. 395–416, 2007.