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Synoris: An unmanned underwater platform based on hydrophone arrays for detection and tracking from sound signatures.

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Abstract—**Sonars have been in practical use since the turn of the 20th century. They are considered to be among the most sophisticated engineering systems concerning detection and tracking. Unmanned underwater vehicles have recently evolved to a higher degree of sophistication with enough processing power to run more demanding artificial intelligence (AI) algorithms. This work is focused on the development of a robust signal processing algorithm on board an Autonomous Underwater Vehicle (AUV), named Synoris, enhanced with target identification capabilities. Synoris is able to perform feature extraction, classification and identification using only on board hardware.**

keywords: UUV, AI, sound, sensors

I. Introduction

One of the greatest challenges Autonomous/Unmanned Underwater Vehicles (A/UUVs) have to overcome is nature itself. Electromagnetic waves get highly absorbed in the water, communications and navigation are either extremely difficult to establish or even inapplicable, therefore the vast majority of underwater drones are remotely operated (ROVs). ROVs rely on a cable connection to communicate with the command station, usually on-board a vessel, where a separate system communicates with satellites for data transmission or geo-location. This is a major drawback since the operational range relies on the cable length; cables cannot be too heavy or wide. This is a logistical problem found in all vessels due to the shortage in space. On the other hand AUVs equipped with acoustic modems able to transmit data at a range from a few meters to kilometers, even though they do not need tethers, the cost is drastically increased due to market shortage. The greatest limitation in the cost-efficiency of UUVs is the dependence to state-of-the-art sensor payloads. Sonars used for target detection or obstacle avoidance and transmission devices greatly amplify the cost of research and development. Target detection in an underwater environment faces great challenges due to physical limitations. The speed of sound in the water is almost five times greater than the speed of sound in the air while electromagnetic propagation through water is very different from propagation through air due to water's high permittivity [1] and electrical conductivity. These facts establish sound as the dominant factor for underwater detection. Synoris [2][3] is built with advanced onboard Sound Signal Processing (SSP) capabilities in order to provide a reliable and state of the art platform for underwater vessel detection.

II. The Synoris design

UUV vehicles have widen their use in recent years, mostly due to to the technological improvements in this field. UUVs have become more sophisticated, more capable and with much more payload carrying capability. [4],[5],[6]. UUVs in general, can be be equipped with various types of sensors and accomplish a wide range of missions including:

- Monitoring, Information Collection and Identification
- Anti-submarine warfare
- Inspection / Identification
- Communication / Navigation Network Nodes
- Oceanography / Hydrography

Synoris was built as a multi-role UUV, medium sized platform, capable of carrying cumbersome or space demanding payload. The flat shape allows for ”bottom looking” sensors while the rear part is carefully designed for hooking up towed equipment such as sonar arrays. Synoris has a maximum depth rate of about 200m making it capable of penetrating the isothermal layer [7]. This feature is critical, as sound tends to be trapped in this layer due to surface reflections and refractions. In the following chapter basic principles, necessary for understanding the SSP (Sound Signal Processing) techniques applied onboard Synoris, will be introduced.

Fig. 1. The Synoris UUV

III. Underwater sound principles

A. Sonar equation

There are many types of equations that describe the passive SONAR problem. They all try to introduce as many parameters as possible for passive sound detection [8]. The format used herein for testing is:

$$L_{S/N} = S_L - T_L - (N_L - D_I)$$

Sound emitted by a target is denoted by S_L. Losses during noise propagation are denoted by T_L. Sound reflected from the bottom is N_L, and direction is denoted by the D_I indicator [9].

B. Signal to Noise Ratio

The signal-to-noise ratio or SNR represents the degree to which an amplifier can be used successfully in providing data to the machine learning algorithm [10]. Whenever the signal-to-noise ratio (SNR) is close to zero, the noise is almost equal to the signal. In this case any amplification will increase both noise and signal resulting to no substantial improvement. For greater values of this ratio, an amplification will improve the signal in relation to noise. A challenge here is to determine the lowest possible ratio value that still leads to acceptable data for further feature extraction. Any measurement above the detection limit is reported as "signal exceeded". Following the relevant bibliography (add reference), a suitable threshold is selected such that a well trained machine is able to spot a target 50% of the time. Note that passive sonar compares *"levels"* (in dB) rather than actual intensities. $L_{S/N}$ is therefore defined as:

$$L_{S/N} = 10 \cdot log\frac{Signal}{Noise}$$

C. Signal level

The signal level received at the detector is the quotient of two quantities on the right hand side of the equation. These are the intensity of the signal emitted by the target and the intensity of the signal received from the source. This logarithm of the ratio is called source level S_L:

$$S_L = 10 \cdot log\frac{I_S}{I_o}$$

I_S denotes the intensity of the signal emitted by the target and I_o denotes the reference intensity. As the signal travels through the water, part of the signal is lost through various mechanisms. The total of this loss is quantified as a dissemination loss.

$$T_L = 10 \cdot log\frac{I_S}{I_R}$$

where I_R is the intensity of the received signal.

The difference between the above two factors determines the amount of signal received at the detector.

$$L_S = S_L - T_L$$

The propagation loss depends on the distance between the source and the receiver as well as some other factors such as absorption etc. Since this distance is very important, the passive sonar equation is adjusted accordingly to include it. The loss that can be tolerated and at the same time still meet the detection criteria, is called the gain margin.

D. Noise level

N_L noise level is the sum of the background and self-noise which reduce the capacity for target detection and is given by the formula:

$$N_L = 10 \cdot log\frac{I_n}{I_o}$$

where I_n the volume of noise [11].

In some cases, D_I which represents direction is also taken into account. It is the ratio of noise detected in a specific direction to the noise in any other direction.

$$D_I = 10 \cdot log\frac{N_{ND}}{N_D}$$

where N_{N_D} is the power of noise from any direction and N_D is the power of noise in a specific direction. When a detector records in each direction, the ratio will be 1, so D_I will correspond to 0 dB. If it is an array of hydrophones, the lobes (directions) formed, introduce *directionality* and the isotropic noise can be compressed.

IV. Underwater Frequencies

A. Environmental Noise

Sub sea environment is quite noisy[12]. In the low frequency range, from about 10 Hz to 300 Hz, the predominant source is the accumulated energy of ships that are too far away to be heard separately. The level of noise emitted by ships contributes to the creation of environmental noise and depends on the distance, traffic, ship routes, and sound energy propagation conditions [13]. In the high frequency range, approximately 300 Hz to 5 kHz, the main source of environmental noise comes from the sea surface (sea state noise) directly related to wind speed, which can be measured. Rain and thunderstorms also increase the level of environmental noise at some frequencies. The characteristic noise produced by rain, ranges from 500 Hz to 15 kHz in frequency. Furthermore, noise from biological organisms also contributes to environmental noise in many marine areas [14]. Due to various acoustic characteristics, some sea areas are noisier than others. The influence of biological activities in the general noise level is greater in shallow waters than in the high seas and greater in the tropics and temperate zones than in colder waters. Finally sea ice is another factor that affects the level of environmental noise. Its influence depends on the condition of the ice, the degree of its formation, the degree of its decomposition and the area it covers.

B. Target Noise

Target noise comes from the main propulsion systems (turbines, Diesel engines, main shaft gears) and the auxiliary equipment of boats (generators, pumps, fans, compressors)[15]. This noise is generated by machines that include rotating or reciprocating parts, as they always do not have some perfectly balanced moving parts. This noise follows various propagation paths and it is finally emitted in the water from the hull of boats[16]. It is captured by hydrophones of the sonar system, either through the platform / carrier itself or after they propagate in the water and it is the most prevalent form of self-noise at low speeds. Propellers are also a main source of noise (hydrodynamic noise, cavitation), due to the non-uniform flow of water around them. Another key component is cavitation noise, which is a strong, continuous wide-spectrum noise, which according to the design of the propeller, extends within a wide frequency range from 10 - 50 Hz up to 100 kHz [17]. Finally the hydrodynamic flow extends in a wide range of noise, which is produced by the relative movement of water around the hull of boats or the vertical movement of sounders in water. It increases with boat speed and the presence of pollution in the hull. Turbulent flow of water, causes additional oscillations of outer hull surfaces. Hydrodynamic noise can be reduced by improving the hull design with smoother lines [18]. Finally, hydrodynamic noise can also be produced by turbulent flow inside pipes and pumps.

V. Sound Signal Processing - SSP

A. Time processing

Humans can hear sound vibrations ranging from 20Hz to 20kHz. Thankfully hydrophones are able to produce recordings way beyond these limits, providing us valuable input for further processing. In this chapter two time-based processing techniques will be introduced, namely, *"Downsampling"* and *"Overlapping"*.

B. Downsampling

The process of reducing a sampling rate by an integer factor is referred to as downsampling. Rate reduction by an integer factor M can reduce high-frequency signal components with a digital lowpass filter and decimate the filtered signal by M [19]. In other words, we keep only every Mth sample of the initial sequence. We assume z(m) = x(mM) to be the downsampled data sequence of the initial x(n), decimated by a factor of M. During this process we must avoid aliasing noise as per the Nyquist sampling theorem [20]. This means

$$fs > 2F$$

(where F is the higher frequency of the sample). The new sampling frequency is fn = fs/M where fs is the original sampling rate. In our case the recorded audio is defined by high sampling frequency so that when we perform a sufficient downsampling, usually by a factor of M = 4, we can create at least four replicas of lower sampling frequency. These replicas contain all the necessary information for feature extraction. The basic idea is that since a target's noise is characterized by very specific frequencies while the surrounding noise is totally random, we can extract information by correlating the replicas. Therefore this procedure allows us to suppress the unwanted noise while amplifying the target's main frequencies.

$$(x_0, x_1, ...) \rightarrow M \rightarrow (x_0, x_M, x_{2M}, ...) = z_1(n)$$

$$(x_0, x_1, ...) \rightarrow M \rightarrow (x_1, x_{M+1}, x_{2M+1}, ...) = z_2(n)$$

$$(x_0, x_1, ...) \rightarrow M \rightarrow (x_2, x_{M+2}, x_{2M+2}, ...) = z_3(n)$$

$$...$$

$$(x_0, x_1, ...) \rightarrow M \rightarrow (x_{M-1}, x_{2M-1}, x_{3M-1}, ...) = z_M(n)$$

Where

$$z_1(n) = (z_{10}, z_{11}, z_{12}, ...)$$

$$z_2(n) = (z_{20}, z_{21}, z_{22}, ...)$$

$$z_3(n) = (z_{30}, z_{31}, z_{32}, ...)$$

$$...$$

$$z_M(n) = (z_{M0}, z_{M1}, z_{M2}, ...)$$

Now that M "replicas" of the initial high frequency signal have been created, a new signal with fd=fs/M is produced, which is much more comprehensive than the initial signal.

$$Z(n) = z_1(n) + z_2(n) + z_3(n) + ... + z_M(n)$$

After performing a Fast Fourier Transform (FFT), it is evident that the frequency generated spectrum has suppressed noise frequencies (due to their random origin) but not the signal generated frequencies as depicted in Figure 2.

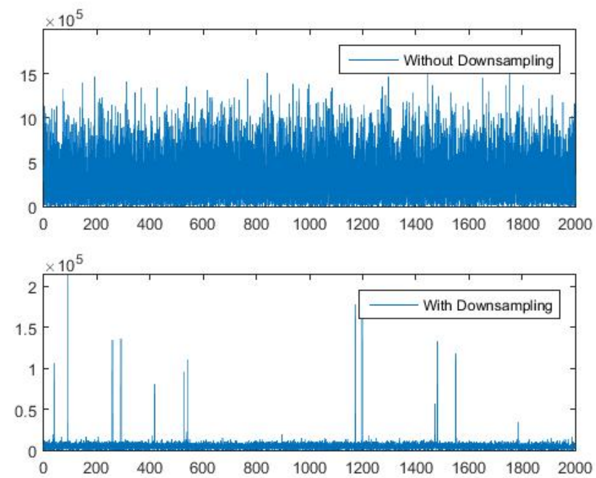


Fig. 2. Noise after downsampling

C. Overlapping

Another time-based technique is Overlapping. The fact that during short time windows, subsea targets generate frequencies steadily and without noticeable differences, can be exploited to improve the smoothness of lofargrams and therefore the quality of output data. By dividing recordings into short time windows and performing FFT to each one separately, small discrete steps of frequency spectrums can be produced. Each spectrum can be correlated to both the previous and next ones, in a way that the final result that feeds the AI is much more accurate. This way, the machine learning algorithm acquires a smoother set of data and improves its results both in terms of accuracy and speed. In Figure 3 an example of this technique is demonstrated, where overlapping is applied to real vessel recordings. Improvements are apparent.

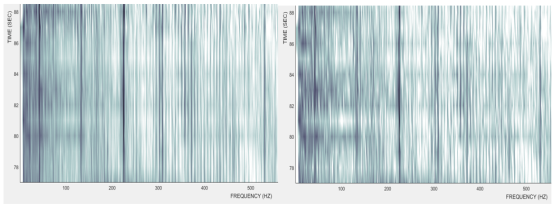


Fig. 3. Lofargram after (left) and before (right) downsampling

D. Space processing

Beamforming is a space signal processing technique mostly used for directional signal transmission or reception. By introducing time delays between hydrophone array elements from different angles one can differentiate based on constructive versus destructive interference. This feature improves reception from specific directions, without having to mechanically steer the array [21]. Whenever a signal is expected to arrive from a specific angle, this type of antenna offers greater efficiency over an omnidirectional alternative. For effective sonar operations, the beam-width and side-lobe structure of the beam steering patterns must be as small as possible in order to achieve high resolution. The following images provide evidence regarding the main lobe shape as it was simulated in Matlab. More array elements give more narrow lobe which leads to better recordings. The majority of omnidirectional noise remains out of the lobe and therefore is suppressed. Another critical factor regarding array sensitivity in specific frequencies is the distance of the array elements as it relates to the desired wavelength. [22].

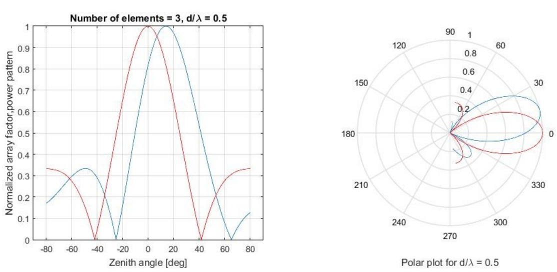


Fig. 4. Main lobe with 3 elements

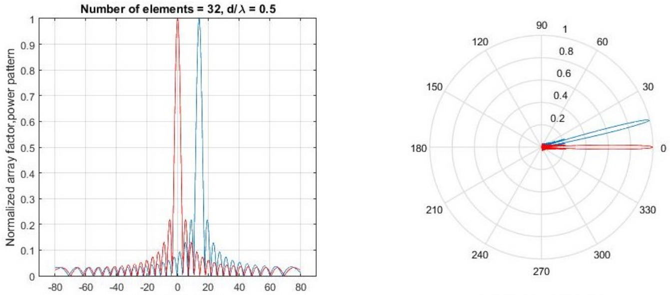


Fig. 5. Main lobe with 32 elements

VI. Experimentation

Synoris ; *named after the chariot of ancient Olympic Games*, is a prototype ”test bed” to exploit sound signatures of surface vessels and submarines, providing a state of the art unmanned sonar platform.

A. Simulation

Before sea trials, a simulation was created in Matlab, so that every possible feature or improvement could have been identified and taken into consideration before construction commences. Since array geometry is extremely important, the user in this simulation has the ability to define several parameters such as the number of array elements and their distance. Furthermore, parameters such as the scanning angle, SNR (Signal to Noise Ratio) and the number of targets are also predefined by the user. Each target's position and it's frequency spectrum is randomly generated by the simulation algorithm. Each spectrum is mixed with a randomly generated surrounding noise before target detection and identification is initiated. After running several simulations with various SNR and number of targets we are able to demonstrate three of the most characteristic results. In the first simulation we provide data for SNR=10. In this case, three targets are placed randomly in relation to the array and their generated noise intensity is much more powerful, making it easy for the algorithm to detect them. The following polar diagram shows that all three targets have been identified.

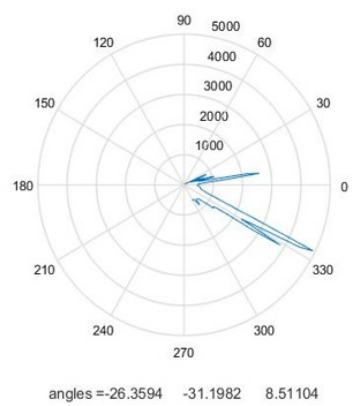
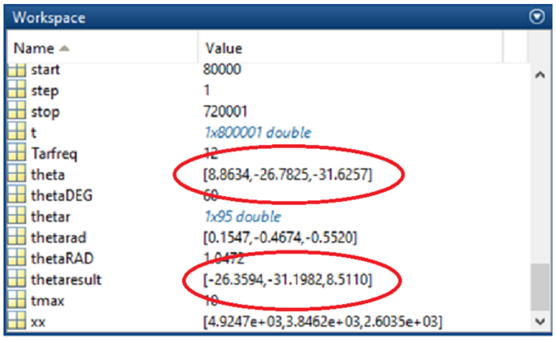


Fig. 6. Detection results with SNR=10

The following table demonstrates theta, which is the initial/actual angle of the targets and theta result which is the estimated one. As one can see the algorithm accurately discovered both the number and angles of targets.



Name	Value
start	80000
step	1
stop	720001
t	1x800001 double
Tarfreq	12
theta	[8.8634,-26.7825,-31.6257]
thetaDEG	60
thetar	1x95 double
thetarad	[0.1547,-0.4674,-0.5520]
thetaRAD	1.0472
thetaresult	[-26.3594,-31.1982,8.5110]
tmax	10
xx	[4.9247e+03,3.8462e+03,2.6035e+03]

Fig. 7. Estimated position of targets

The second simulation was run for SNR=0 which means that the noise is as powerful as the targets. Once again the algorithm was successful, as the estimated positions are very accurate.

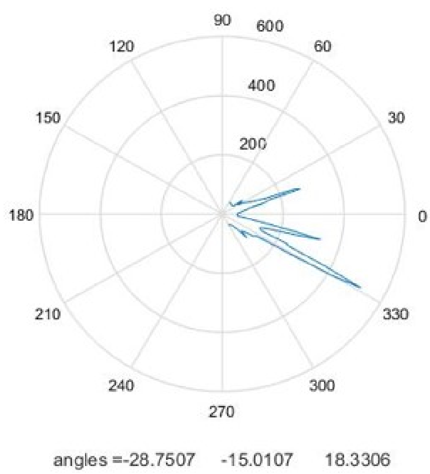
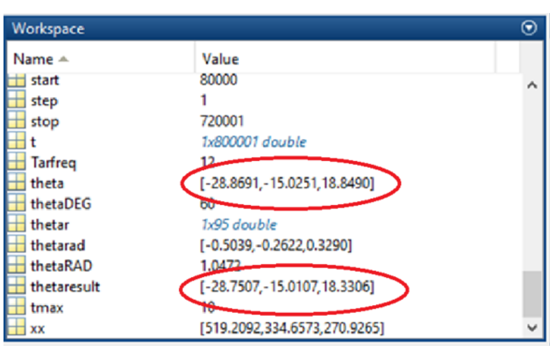


Fig. 8. Detection results with SNR=0

The following table shows that the detection algorithm, once again managed to extract the features of all targets together with their relative directions.



Name	Value
start	80000
step	1
stop	720001
t	1x800001 double
Tarfreq	12
theta	[-28.8691,-15.0251,18.8490]
thetaDEG	60
thetar	1x95 double
thetarad	[-0.5039,-0.2622,0.3290]
thetaRAD	1.0472
thetaresult	[-28.7507,-15.0107,18.3306]
tmax	10
xx	[519.2092,334.6573,270.9265]

Fig. 9. Estimated position of targets

The final simulation provides evidence on the limits of this detection algorithm. It was run for SNR=-25, which is a very challenging situation considering that the noise is much more powerful than the signal.

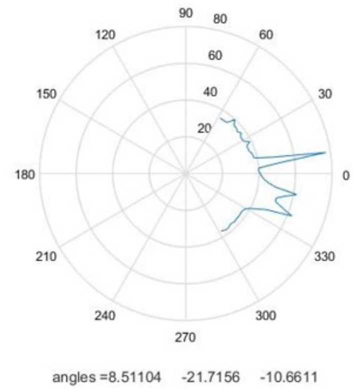
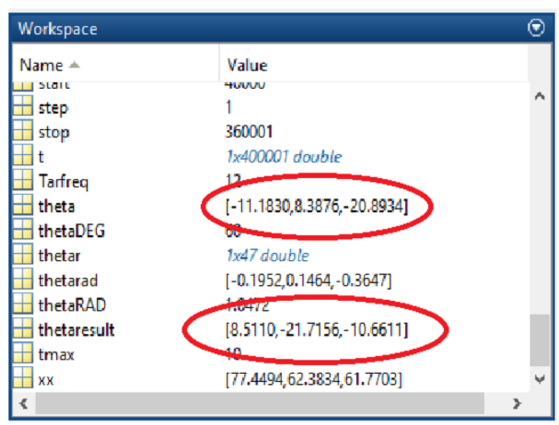


Fig. 10. Detection results with SNR=-25

As is obvious from the diagram, the noise was too powerful to suppress but once again the signal was distinguishable. As the following table suggests, the estimated angles are still acceptable regarding the harsh conditions. Further decrease of the SNR showed that detection was still possible but the uncertainty raised rapidly, making the results unfitted for reliable operational use.



Name	Value
start	40000
step	1
stop	360001
t	1x400001 double
Tarfreq	12
theta	[-11.1830,8.3876,-20.8934]
thetaDEG	60
thetar	1x47 double
thetarad	[-0.1952,0.1464,-0.3647]
thetaRAD	1.0472
thetaresult	[8.5110,-21.7156,-10.6611]
tmax	10
xx	[77.4494,62.3834,61.7703]

Fig. 11. Estimated position of targets

B. *Synoris prototype*

During the last decades UUVs have revolutionized the field of ocean research [23] by transforming heavy and expensive equipment into more portable and easily deploy-able resulting in lowering costs and increasing versatility. Under this scope Synoris is a medium AUV, developed as a low-cost platform for acoustic target detection, *carrying* an array of hydrophones, hence the name of the ancient Greek chariot. A renowned case of using hydrophones was in the localization of the missing Argentinean submarine *ARA San Juan*, using the hydrophones network of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO)[24][25].

C. Validation

Synoris team conducted several field trials in order to collect real data and evaluate the algorithm under most realistic scenarios. The following results were generated after a civilian vessel conducted several passings during a relatively smooth sea state. In the polar diagram it is shown that the direction of the incident wavefront is estimated to be theta=13.57 degrees. This is a very accurate estimation and meets all the predefined criteria for acceptable performance.

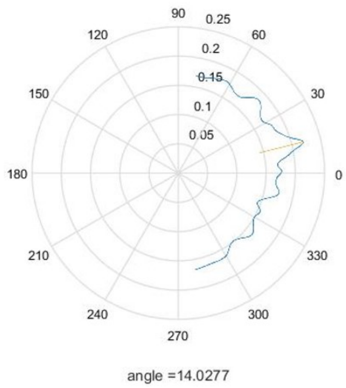


Fig. 12. Estimated position of target

Figure 13 is a snapshot of the lofargram produced after applying all the aforementioned techniques. Noise is very well suppressed and target frequencies are quite well enhanced. An experienced and well trained sonar operator can easily extract valuable information regarding which frequency is generated from the propeller, hydrodynamic flow etc. Similarly, after processing various recordings, the machine learning algorithm was able to identify the vessel as a rigid inflatable boat.

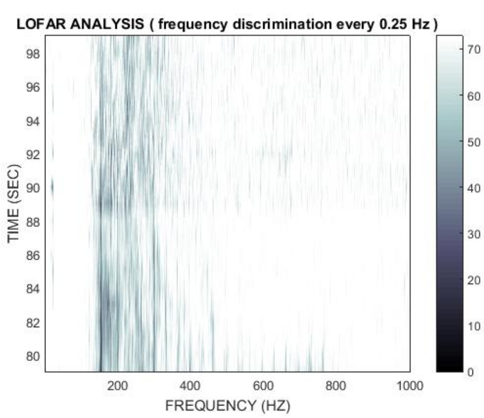


Fig. 13. Lofargram of target

VII. Conclusion

The use of unmanned systems in aiding or conducting critical underwater operations is becoming widespread thus designing state of the art AUVs such as Synoris, offers a great service in reducing operational costs and the risk for human lives. Although in prototype stage, Synoris is a low cost AUV platform capable of performing complex AI related duties such as feature extraction, classification, identification etc and has proven capable in executing hi processing power tasks. This type of vehicles can be a game changer in the field of target detection or environmental/Biological sound signal processing since constant advances in hardware are directly employable to their improvement.

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