Port entrances, nuclear power plant cooling water in- and out-flows, military piers, shore-based manufacturing plants, shipyards, oil platforms—all are potentially vulnerable points of entry for intruders. The intruding force could be a swimmer, diver, unmanned underwater vehicle, submarine, or surface watercraft. Acoustic detection of intruders approaching in the waterway would give security personnel time to potentially prevent the attack on the facility before it occurs. At a minimum, knowing about a pending attack could even save the lives of facility personnel.

Underwater vector sensors and vector sensor arrays can improve the detection and localization of acoustic signals compared to conventional omni-directional hydrophones and hydrophone arrays. They could be particularly useful in monitoring underwater acoustic noise near the above-mentioned strategic points of interest. Vector sensors by their nature provide a steerable directional beam that measures the magnitude and direction of acoustic signals while providing a null that steers toward a known interfering noise source. Small arrays of vector sensors can provide increased gain against isotropic and directional noise as well as enhanced localization resolution.

Unlike the open ocean, a port or waterway is a noisy environment. Typical noise sources include commercial shipping vessels, recreational boating traffic, and stationary underwater noise sources such as cooling pumps. These sources can easily mask the acoustic signature of an approaching intruder—nearly thwarting the job of the underwater sensor. The U.S. Navy's surveillance sensor is the omni-directional hydrophone. This sensor has seen use in a variety of applications including towed arrays, stationary arrays, hull-mounted arrays, and sonobuoys. An omni-directional hydrophone is a pressure sensor designed to sense acoustic pressure equally in every direction. Unfortunately, this feature reduces the sensor's ability to detect acoustic signals from an intruder that are quieter than the surrounding noise sources.

One way to combat this problem is to use a directional sensor such as an underwater vector sensor. A vector sensor includes three uni-axial accelerometers and an omni-directional hydrophone. The accelerometers measure acoustic particle velocity in each independent axis. The measured velocity provides the directional capabilities of the sensor. The Navy has wanted this type of sensor for a long time because of its ability to give directional information on target noise sources and to ignore other known noise sources.

Vector sensors
To measure particle velocity in the water, the vector sensor must be neutrally buoyant in the water—hovering in the water column. Developing a highly sensitive, low-noise, vector sensor in a small, neutrally buoyant package suitable for Navy surveillance applications was not possible using existing piezoelectric materials. However, a new piezoelectric material, lead magnesium niobate/lead titanate (Pb(Mg1/3Nb2/3)O3-PbTiO3), known as PMN-PT crystals, has made it possible to develop such a sensor. The piezoelectric properties of the material are 7–10 times greater than conventional piezoelectric ceramic materials, such as lead zirconate titanate (PZT). This increase in the piezoelectric properties of the material allows the sensor designer to reduce the weight and size of the sensor while maintaining a specific sensitivity and signal-to-noise ratio.

There's a way to harness the electromechanical properties of the PMN-PT crystals to develop a miniature vector sensor for towed array applications. This particular sensor has operational bandwidth from 5Hz–7kHz with a noise floor that crosses a sea state 0/shipping level 1 noise curve at approximately 1000 Hz for the accelerometers. The omni-directional hydrophone element (which uses conventional PZT) is quieter than the sea state curve across the entire frequency band.

The directional capabilities of the vector sensor stem from the dipole behavior of the individual accelerometers. Each accelerometer is extremely sensitive only along a specific axis while being insensitive in the other two axes. The resultant beam pattern for this type of
accelerometer is a dipole pattern. The sensor provides near-theoretical sine/cosine responses with deep nulls and very nice main lobe linearity. Each null is at least 30 decibels (dB) down from the main lobe of the dipole. This equates to an off-axis or transverse sensitivity of ~3% relative to the main lobe. This type of off-axis sensitivity is essential for directional hydrophone signal processing.

A method of defining a sensor’s ability to discriminate against noise coming from directions other than that of the target is called the directivity index (DI). You'll typically find the DI listed in dB. It's the amount of sound power that a sensor rejects compared to an omni-directional sensor and a directionally random or spatially isotropic noise field. A single vector sensor can provide 4.8–6.0 dB (or 300–400% power reduction, respectively) of signal-to-noise ratio gain due to its DI. In contrast, an omni-directional hydrophone would provide no gain or a linear gain of 1, which equates to a DI of 0 dB. You can even realize higher DIs from a vector sensor in nonisotropic ambient noise fields such as those wind-induced waves create in shallow water.

Since each vector sensor has an omni-directional hydrophone and three uni-axial dipole accelerometers, it can form a dipole and cardioid response in any arbitrary direction. The dipole and the cardioid responses will be directional and will also have a deep null in a particular directional. The graphic at left shows theoretical beam patterns that could form from a single vector sensor along with the respective DIs in an isotropic noise field. The highly sensitive portion of the dipole or cardioid beam pattern would point in the most probable direction or location of the target acoustic source—in this case a water-borne intruder.

The insensitive null in the dipole and cardioid beam patterns would steer toward a known, interfering noise source so that the vector sensor would reject it and virtually eliminate it from the sensor’s sound field. The ability of the vector sensor to listen in a particular direction while ignoring other noise sources is a major advantage for the sensor in this application.

**Vector sensor arrays**

Small arrays of vector sensors can also provide significant gains against broadband and narrow-band noise interference. Here broadband refers to noise that covers a significant portion of the audio frequency band, such as that from wind-induced noise. Narrow band refers to sound from tonal-type sources, such as that emitted from rotating machinery. An array is a group of sensors spatially separated.

Arrays also provide significant directivity due to their spatial coverage. The figure at bottom left shows predicted beam patterns and array gains for a simple five-element linear array. Such an array is relatively small (<6 ft. long). You can easily install it near choke points or protected assets. At 90% of the design frequency of the array, the cardioid array would provide up to 11.4 dB of gain in an isotropic noise environment. An equivalent linear omni-directional array would require over 15 hydrophones to achieve the same gain.

The design frequency of an array is the frequency at which half an acoustic wavelength equals the array spacing. Small arrays of vector sensors can provide detection, classification, and localization of underwater acoustic signals. You can use adaptive beam forming with the array of vector sensors to automatically null-out known, loud interfering sources without significantly compromising detection capabilities in other directions, provided an adequate signal-to-noise ratio exists.

In this example, the array would steer electrically to calculate the pressure arriving from different receive angles. Levels significantly higher than the background or matching a known signature would constitute a detection, automatically alerting the operator. To account for shallow water propagation effects that distort the otherwise free propagation of sound, you can employ ocean acoustic models such as OASES and incorporate them into the beam-forming algorithms. You can also use experimental approaches, such as training the array to detect targets in specific locations. In the latter case an active acoustic source at a known location would transmit broadband signals that the vector sensor array measures. You would then use the necessary steering vectors or the information needed to properly sum the sensor outputs coherently to train the beam-forming system.

**Behind the byline**

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