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CVL Array Lessens Cost, Complexity by Streamlining Receiver Redundancy

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By Dr. Jeremy Dillon

Underwater navigation is essential for a diverse range of applications, such as subsea surveying, safe operation and recovery of UUVs, swimmer delivery systems, and naval mine hunting and neutralization. The increasing use of UUVs throughout the past decade has seen significant advances made in the range of available sensors and subsystems. Advanced payloads have been the main focus for overall development as operators look to expand the capabilities of vehicles and to undertake missions that were not previously considered safe, effective or economical. This has led to new and innovative payloads being developed, which are constantly being reduced in size and weight while offering greater capability and value. This is especially true for acoustic sensors.

Although GPS and other radio signals have been widely used for surface vessel navigation, these technologies are ineffective for underwater navigation, because electromagnetic waves are blocked by seawater. Inertial sensing is a suitable and widely used technology for autonomous underwater navigation. However, the position error tends to drift in the absence of input from an aiding sensor. The most successful combination for underwater navigation has therefore been to combine inertial technology with velocity measurement from an acoustic sensor that measures speed from echoes reflected from the seafloor.

Acoustic velocity sensing is a dual-use technology with many commercial applications, in addition to military ones, such as mine countermeasures. As UUVs become an integral component of a modern naval force, spending on payloads for intelligence, surveillance and reconnaissance (ISR) missions continues to be significant. In addition, the use of sensor technology has seen a greater focus on imaging, navigation and communication for payloads capable of relaying real-time and relevant information to other units. Leading-edge research and development for the military market has in turn led to a greater emphasis on the civilian use of UUVs, with applications including surveillance, imaging, detection and mapping for commercial sectors, such as offshore energy as well as ocean science and marine archaeology. Commercial applications include offshore and deep offshore geophysical survey and construction support as oil is being discovered and extracted in deeper water beyond the continental shelf.

Doppler Velocity Log

The majority of in-service acoustic velocity logs exploit the Doppler principle, which is the frequency shift of the seabed or seawater echoes due to the relative motion of the sonar. A typical Doppler velocity log (DVL) consists of four narrow beams steered in the fore/aft and port/starboard directions to estimate the 3D velocity vector from Doppler shifts associated with each beam. The beams are steered

The AquaTrak correlation velocity log produced by Kraken Sonar Systems Inc. of Canada.

"The minimum redundancy array design significantly reduces the overall number of sample channels required, resulting in lower power and more compact electronics."

downward approximately 30° from vertical in a compromise between operating near nadir to maximize seabed echo strength, while also requiring a non-zero Doppler shift when measuring the horizontal component of velocity. This is a well-established and widely used technique, but it becomes increasingly inaccurate at low speeds.

The most common configuration of DVL employs four separate piston transducers to form the four sonar beams. In order to resolve a velocity vector from DVL acoustic transmissions, the angle of the corresponding seabed echoes must be known precisely, which requires the use of narrow beams. This leads to a relatively large sensor with an unavoidable trade-off between size and range. For example, when operating at 300 kilohertz, each piston must be on the order of 5 to 10 centimeters in diameter to achieve a beamwidth of a few degrees. This gives an overall diameter of about 20 centimeters for a DVL operating at 300-kilohertz frequency for which the range is approximately 200 meters, which is less than that required for operation over the whole continental shelf. The only way to reduce DVL size without compromising accuracy is to increase the operating frequency at the price of a greatly reduced range due to the increase in sound absorption. At 1,200 kilohertz, the DVL size can, in principle, be reduced by a factor four compared to 300 kilohertz. However, the range at 1,200 kilohertz is drastically reduced to only 30 meters.

Another limitation of the traditional DVL is the trade-off between narrowband and wideband signaling techniques. While narrowband transmission allows for a very simple detection of the Doppler frequency shift (e.g., as the centroid of the spectrum of the echo), the lack of range resolution leads to an inability to resolve fine spatial gradients in the current profile, as well as increased variance in the velocity estimate. The variance can be reduced by averaging over an ensemble of pings at the price of reduced temporal resolution, but the system is then no longer able to track fast changes in velocity with time. Wideband measurement techniques were developed in the late 1980s to overcome this limitation. However, for wideband DVLs, there is a further decrease in the operational range of the system due to the increased noise bandwidth and the corresponding decrease in signal-to-noise ratio, which exacerbates the range limitation from acoustic absorption. Thus, DVLs are offered either in a high-resolution, short-range mode using wideband pulses or a low-resolution, longer-range mode using the more traditional narrowband mode.

Another drawback of the multipiston DVL is that the Doppler frequency shift depends on the local sound speed, which in turn depends on temperature, depth and salinity. While it is relatively easy to measure depth and temperature, salinity requires a more complex conductivity sensor, which adds to the size and cost of the overall navigation package. In the absence of a conductivity sensor, sound speed errors as large as 4 percent can be observed, especially near estuaries. This would lead to position errors of more than 200 meters after one hour of navigation at 3 knots in such waters. While a phased array may be used in place of multiple pistons to combat the sound speed dependence, the price to pay is an increase in complexity and cost, since the phased array must be populated with half-wavelength element spacing in order to form the same narrow beams as the multipiston head. For example, a matrix on the order of 1,000 elements is required to achieve 4° beams, and 16,000 channels would be required to further narrow the beams to 1°. Thus, phased array DVLs face a similar trade-off between size and range as encountered with conventional DVLs.

Correlation Velocity Log

Another acoustic technology for underwater velocity measurement is known as the correlation velocity log (CVL). The application of the correlation technique to speed measurement is not new. Originally proposed in the 1950s for use with radar, it was used with sonar with some success by General Electric (Fairfield, Connecticut) and others in the 1970s. The fundamental concept is still best described in the words of the pioneers Dickey and Edward (1978): "The objective, in the correlation system, is to transmit two identical signals separated by a known time interval and then to search for a separation vector and a time delay for which the correlation (of the received signal) is a maximum."

Using modern synthetic aperture sonar signal processing techniques, CVLs are now poised to compete in traditional DVL navigation markets. A CVL transmits pulses vertically downward with a much broader beam than used for DVLs. The reflected signal is recorded by two or more receivers separated by a few centimeters. Two variations exist: a temporal log searches for the time delay that maximizes the correlation between a pair of receivers, whereas a spatial log finds a receiver pair that maximizes the correlation for a fixed time delay (typically the time interval between successive pulses).

In either case, the velocity estimate is found by dividing the known distance between receiver elements by the correlation time delay. The broad beam of a CVL is achieved using relatively low frequencies where reduced acoustic absorption, coupled with strong seabed echoes for a vertical beam, provide a step change in the sonar range compared to DVLs of similar size. This greatly increases the navigation accuracy at high altitude above the seabed. For example, the CVL increases UUV operating ranges from 30 meters to greater than 300 meters, enabling surveys of the entire continental shelf with continuous aiding of the vehicle inertial navigation system. Another important advantage of the CVL over the multipiston DVL is that the measurement of velocity in the plane of the array (i.e., the horizontal component, in the absence of pitch or roll) does not depend on the speed of sound. By its principle of operation, a CVL measures a 2D displacement vector between two receiver channels for successive pulses, so that the corresponding velocity measurement is given simply by the displacement divided by the time interval between pulses, with no need for a speed-of-sound measurement.

CVL Challenges

To date, only comparatively large CVLs have been developed for long-range operation (300 meters or more) for large platforms using low-frequency signals in the range of 30 to 75 kilohertz. The main factors that have limited widespread adoption of CVLs on small platforms are the signal processing and requirement for miniaturization. Recent advances in low-power electronics have made it possible for CVLs to reach their full potential across a wide spectrum of applications.

Another challenge in CVL development is selecting an optimal design from the wide variety of possible configurations for the receiver array. Unlike DVL designs that are essentially identical except for minor variations (e.g., three piston transducers instead of four), a CVL can be constructed with any number of elements in a planar array. Fortunately, it is not necessary to fully populate the array, which drastically reduces the number of elements compared to a phased-array DVL. In order to accommodate a wide range of operating conditions, including speed and heading changes, previous designs have used on the order of 10 to 30 receiver elements to provide many distinct displacement vectors for correlation processing.

AquaTrak

A CVL product named AquaTrak, developed by Kraken Sonar Systems Inc. (Conception Bay South, Canada) features a new array design that eliminates redundant receiver pairs to minimize the sonar size, complexity and cost. By combining the latest low-power electronics with advanced signal processing algorithms from synthetic aperture sonar, the AquaTrak CVL is significantly more compact and power efficient than existing DVLs while achieving a maximum altitude greater than 300 meters above the seabed. In early April 2015, the AquaTrak underwent further sea trials in and around Portland Harbour, England. The unit successfully tracked velocity relative to the seabed from altitudes of less than 1 meter to more than 50 meters (limited by water depth).

The innovative AquaTrak transducer design was demonstrated to provide robust measurements of displacement and velocity, at a variety of speeds. The minimum redundancy array design significantly reduces the overall number of sample channels required, resulting in lower power and more compact electronics.

AquaTrak was also proven to be robust against platform stability, providing measurements independent of pitch and roll oscillations due to high-sea states. It was also shown to provide velocity measurements independent of water temperature and salinity, demonstrating the independence of the correlation velocity measurement from sound speed.

Conclusion

CVLs offer advantages over DVLs in many UUV applications, since they can achieve high accuracy at low velocities—even during hover maneuvers. DVLs require narrow beam widths, while CVLs have wide beam widths. This gives CVLs the potential to use lower frequencies, thus permitting operation in deeper water, reducing power requirements for the same depth while also increasing accuracy and range.

DVLs have traditionally been the instrument of choice for interfacing to inertial navigation systems for UUV navigation. Rather than detecting Doppler shifts in the acoustic echoes from the seabed, the CVL searches for similarities in the signals detected across a receiver array. It estimates velocity of the vehicle based on spatial separation vector corresponding to maximum correlation between receivers and the time interval separating a pair of acoustic pulses directed at the seafloor.

In the future, both CVLs and phased-array DVLs will likely be in widespread use for underwater vehicle navigation. With the expiration of a patent for the underlying broadband technology of most existing DVLs, the market can look forward to an increase in competition and lower costs for the classic DVL design. However, technology has advanced considerably during the past two decades, and recent progress in CVL design is poised to finally achieve the right balance of price and performance in a compact form factor for UUVs. **ST**

Dr. Jeremy Dillon is senior technology adviser for Kraken Sonar Systems Inc. Dillon's area of expertise is advanced signal processing for interferometric synthetic aperture sonar. He is presently working on algorithms for guidance, navigation and control of UUVs.