COVELIA - A CORRELATION SONAR VELOCITY SENSOR

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ABSTRACT
Position finding is a significant problem in the operation of underwater vehicles. While surface vessels can rely on GPS to provide accurate position information, sub-sea vehicles either use techniques that locate position relative to external objects or those that calculate position from measurements of the vehicle’s acceleration or speed. A substantial proportion of the Earth’s surface lies under water and has not been explored, and therefore there is clearly a need for an accurate positioning instrument for this environment.

This paper describes the development of an entirely new correlation sonar velocity sensor aimed specifically at the rapidly maturing market for AUV platforms and associated instrumentation. The chosen implementation places particular emphasis on producing a product with very high accuracy, vector velocity output which is maintained down to zero speed and when operated in a hover manoeuvre. Other essential features of this velocity sensor are its small size and low power budget.

The features, advantages and proposed uses of the new velocity log, together with a description of the hardware system and the sensor development are discussed. Results from lake and sea trials are presented which demonstrate the system’s capabilities.

INTRODUCTION
Correlation velocity logs (CVLs) have the potential to improve the navigational performance of AUVs significantly, particularly in low speed conditions. However, difficulties in producing a CVL in a form suitable for AUVs, combined with limitations associated with a basic implementation of the CVL concept has so far limited their use. This paper describes the development of a new CVL that incorporates significant technical innovations designed to produce a high-performance navigation aid able to operate in a wide range of conditions and to be compatible with the particular requirements of the AUV market.

Advantages of a correlation velocity log
Surface vessels can measure their velocity and position using methods based on electromagnetic wave transmission such as satellite positioning (GPS). These systems will not work below the surface because water acts as a Faraday cage. Systems that measure position from sonar transmitters or targets at known locations are classified as long or short baseline, while techniques which do not require such targets include inertial navigation systems (INS), the Doppler velocity log (DVL) and the CVL [1,2,3].

Inertial navigation systems measure the acceleration and rotation of a vessel and calculate velocity by integration. Any bias errors therefore accumulate and reduce the overall accuracy of the system. The Doppler velocity log measures the Doppler shift of sonar signals reflected off the seabed to obtain the velocity of the vehicle. This is a well-established and widely used technique, but becomes increasingly inaccurate at low speeds.

The CVL is similar to the DVL in that it uses sonar echoes from the seabed, but in the CVL the acoustic beam is broad and directed straight down toward the seabed. This makes the CVL relatively insensitive to unstable platform motion, enables smaller, lighter transducers to be used at a given frequency, and the shorter propagation path requires lower source levels and hence lower overall power usage. It also allows the CVL to use a lower acoustic frequency than the DVL, and therefore increases the range of operation. The CVL is not dependent on the speed of sound and takes direct measurements of vessel displacement.
between successive sonar transmissions making it highly accurate at low speeds, where other methods based on velocity or acceleration measurements are prone to errors.

**Potential uses of the CVL**

Existing CVLs have largely been developed for the defence market. The system described in this paper is aimed primarily at the AUV market, as this CVL is particularly attractive to vehicles operating at low speeds and with restrictive power and weight requirements. This includes those designed for mine-hunting operations, cable and pipeline examination, and seabed mapping applications.

The system (named COVELIA) aims to provide position information that is accurate to within 30m after 24 hours; this equates with an error of less than 0.1% in velocity measurement at 1 knot, and heading measurement accuracy (over long term) better than 0.05°.

**The CVL Principle**

In its most basic form, a CVL consists of a sonar transmitter and a number of receivers. In the configuration used here, two short sonar pulses are emitted, reflected off the seabed and the echoes measured on the receiver array. The received signal is formed by the superposition of the individual echoes from each of the features, or scatterers, on the seabed. The signal obtained at each receiver is determined by the distribution of scatterers on the seabed and the distance between the receiver and the scatterers. Each signal will be slightly different from that measured on the neighbouring receivers. Comparison of the sets of received signals from the first and second pulses shows that the pattern of signals is shifted across the receiver array by an amount determined by the displacement of the vehicle in the time interval between the two pulses. Hence, if the first signal arriving at a receiver is compared with the second signal arriving at all other receivers in an array, the distance between the transducers registering the most similar signals is directly related to the distance the craft has moved in the interval between the pulses.

The similarity between signals is assessed by calculating a correlation coefficient for each pairing. This varies between −1 and +1. A value of +1 implies good agreement, 0 implies no agreement and −1 means that the two signals are 180° out of phase. Figure 1 shows an example of received signals. The echo from the first pulse is measured on the first receiver and compared with the received echoes from the second pulse measured on receivers 1-4. The correlation coefficient is calculated for each of the four pairings and the highest value indicates the best agreement. In this case, the distance moved between the pulses is calculated using the distance between receiver one and receiver three (the correlation peak). Under idealised conditions, the peak value should be +1; however, effects such as noise may reduce this value. The peak may lie between receivers and therefore peak finding methods are employed. The position of the peak is used to calculate the velocity of the vehicle.

Velocity measurements in two directions can be obtained using a 2D array of transducers. COVELIA uses a 2D array with irregular transducer layout; this provides a wider range of inter-receiver distances and greater resolution is obtained. A feedback loop adjusts the interpulse interval and selects the receiver pairings to use in the correlation process, based on the current vehicle velocity.
On power-up, or if operation is interrupted, a search procedure is performed to obtain an initial estimate of the velocity, which can then be used in the feedback control.

The accuracy can be improved by making use of the synergy between an INS and a CVL. The short-term accuracy of the INS can be used to stabilise the feedback control of the CVL, while the accuracy of the CVL over the long-term improves the INS output by minimising the accumulation of integration errors. This provides a velocity output that is significantly better than that obtained from either sensor by itself.

OVERVIEW OF CVL DEVELOPMENT

COVELIA has been developed in a joint commercial venture between Marine Acoustics Ltd and H Scientific Ltd, with collaboration from the University of Southampton.

Computer simulations have been used extensively throughout the development of COVELIA, to investigate the fundamental processes and optimise the control algorithms. Three models have been used; these are described in the following paragraphs.

The physical processes have been modelled on a ping-by-ping basis using a model that simulates the pulse transmission, reflection and receiver response, and calculates correlation coefficient distributions. This model has been used to investigate the performance over a range of depths, seabed parameters, as well as transducer properties on the correlation data. Continuous collaboration and communication between the hardware development and the simulation have ensured an accurate and realistic model.

A macroscopic model simulates the behaviour of the CVL on a longer time scale, allowing assessment of the long-term accuracy. The model simulates the movement of an AUV around
a user-defined track, subjected to random currents and wave motions, and incorporates empirical relationships for the correlation coefficient distributions established using the detailed model. This model has been used to assess different transducer layouts and was used to obtain the layout used in COVELIA. Key algorithms were tested using this model before being incorporated in the evaluation system. The model has also been used to investigate the effects of manufacturing tolerances, such as in the transducer locations, and properties, and the alignment of the array, over a long time scale. Emphasis has been placed on factors that cause systematic errors; these represent a greater threat to the long-term accuracy than random pulse-by-pulse errors.

During the testing programme, the ‘Ship Sim’ simulator (developed by H Scientific Ltd and commercially available) was extended to include a CVL instrument model. Ship Sim is a fully configurable ship simulator, which can be used either in ‘simulator’ or ‘monitor’ modes. As a simulator, Ship Sim models the movement of the vessel in response to on-screen machinery controllers (e.g. sliders to control engine, rudder) or by autopilot control (e.g. heading, track control). Environmental effects such as wind, tide, and sea-state are included, together with navigational instruments, such as the GPS and the compass. In the monitoring role, Ship Sim monitors and logs the performance of a real boat or, indeed, a simulated vessel. Ship Sim is used in this way to interface with COVELIA and log the information from the reference navigational instruments during the hardware trials. In the simulation trials, the monitoring computer is used in the same way, and a second computer is used to simulate the movement of the trials vessel and the CVL and other instruments. This is shown schematically in Figure 2. This is highly efficient way of testing the control algorithms within the CVL and the interfaces with other navigational instruments, thereby saving valuable time in the lake and sea trials.

**Hardware description**

The component parts of COVELIA are illustrated in Figure 3 and Figure 4. Figure 3 shows the four PCB’s that form the signal-processing suite while Figure 4 is the transducer array. The signal processing electronics fits within a cylindrical pressure housing with two connectors mounted at one end. One connector mates to the transducer cable while the other outputs velocity data and interfaces to the platform navigation processor. The electronics pod is 100mm in diameter and 230mm in length while the transducer array measures 330mm by 220mm by 70mm. The computational heart of the sonar is made up of an FPGA chipset coupled to a parallel processing DSP engine. Communication with other instruments is provided via a proprietary NMEA sentence.

A very compact product packaging envelope has been achieved and this is allied to the use of low power electronics to produce an overall system very suited to AUV deployment where space and power availability are often at a premium. These are areas where the correlation log concept scores significantly when compared with Doppler log alternatives. COVELIA is often required to function from a dedicated, battery power supply. The standard voltage for this supply is 24V with a corresponding, average current consumption of 0.125Amp. Thus, for a typical AUV operation spanning 12 hours, the total battery requirement is only 3.0Ah.
HARDWARE TEST PROGRAMME

Hardware trials have been carried out over the last 18 months, in a lake, on the Solent and in the Bristol Channel. In each case, the sonar array was fixed rigidly to the trials vessel and located away from the vessel’s wake and 0.5-1m below the surface.

Each location has its own particular advantages. Many hours of trials data have been obtained in lake trials throughout the programme; the lake floor is sand/gravel and the depth varies between 8-15m. The Bristol Channel provides a wider range of sea-floor types (sand/gravel, rock, fluidised mud), and the Solent provides a wider range of depths.

The CVL measures the velocity relative to the sea floor in its own co-ordinate system and therefore requires accurate heading information to convert this into global North East co-ordinates. In addition for the trials, an independent position or velocity measurement system is required for comparison with the CVL output. The reference system used during trials comprised a GPS and a compass. Where available, an RTK DGPS and gyrocompass have been used, however, these were unavailable in the lake trials and a hand-held GPS and fluxgate compass were used.
Errors in the GPS position data arise from a number of causes including atmospheric disturbances; the Garmin 12 GPS used in the lake trials has a quoted accuracy of 15m (RMS). The position resolution is just over 1m (East) and 1.85m (North); the velocity is calculated by filtering the position differences. The fluxgate compass is gimballed and is subject errors during rapid turning and sea state motion. It is also affected by the proximity of ferrous metals and electromagnetic fields, although a calibration procedure is performed at the outset of each trial to reduce these errors.
TEST RESULTS
Three methods have been used to compare the data from COVELIA with that from the GPS and compass, as follows:

- Speed comparison (CVL against GPS),
- Course over ground (CVL plus heading, in comparison with GPS data), and
- Position (CVL plus heading, integrated, in comparison with GPS data).

In order to obtain these data from the measured data, the following calculations are performed:

- GPS measured position adjusted for the offset between the location of the GPS and that of the CVL,
- GPS velocity obtained from GPS position (filtered); hence speed and COG,
- CVL velocity combined with heading to obtain COG and velocity in global (NE) co-ordinates, and
- CVL velocity, converted into global co-ordinates using heading, and integrated, to give position.

The following figures show the results obtained during lake tests, firstly, comprising a series of approximately straight-lines, followed by some ‘S’ manoeuvres (over a 35 minute period), and secondly consisting of a diverging spiral.

The COG and speed measured during the first set of manoeuvres are plotted in Figure 5, showing that COVELIA tracked the velocity well, with good agreement in COG and speed. The average error in COG was $-0.3^\circ$ (standard deviation of $4.7^\circ$), while the average error in speed was 2.2%, standard deviation of 8.5%. At the end of the set (after 38 minutes and a total track length of 4473m), the overall difference between the position measured by the GPS and that calculated from CVL data was 3.3m (less than 0.1% of the track length).

In the absence of wind, currents or tide, when the trials vehicle is motoring straight ahead, the course over ground will coincide with the heading. However, during turns, the vehicle will develop a significant sideways component of velocity. It is this angle between the course over ground and heading that is measured by the CVL; this is referred to as ‘course over ground in transducer co-ordinates’ (COGT). The purpose of the diverging spiral was to subject COVELIA to a time varying COGT.

Figure 8 shows the position recorded by the GPS during the diverging spiral manoeuvre, together with the position calculated from the CVL velocity. This demonstrates the resolution in the GPS output; this, combined with the fact that this was a relatively slow manoeuvre, explains the jumps in the speed and COG plotted in Figure 7. At the end of the manoeuvre (4.5 minutes, track length 285m), the overall offset between the position obtained from the CVL data and the GPS measured position was 0.9m. COVELIA was operating at a measurement frequency of 1Hz; increasing this rate will improve the accuracy during manoeuvres which include varying speed and direction.
Figure 5: Comparison between CVL (+ compass) and GPS speed and course over ground (leg 1)

Figure 6: Comparison between CVL (+ compass) and GPS position (straight line + S)
Figure 7: Comparison between CVL (+ compass) and GPS speed and course over ground (diverging spiral)

Figure 8: Comparison between CVL (+ compass) and GPS position (diverging spiral)
CONCLUSIONS
A correlation velocity log has been developed specifically for the AUV market, which provides accurate velocity measurements at low speeds by incorporating a number of innovative features. This, combined with small volume and low current requirements, makes the new velocity log highly suitable for AUV use.

Extensive computer simulation has been carried out to obtain a thorough understanding of the behaviour of the system. This has been used to optimise the hardware design and to investigate the effect of the operating conditions and processing methods on the long-term accuracy. A robust procedure has been used which improves the efficiency of the development and testing programmes.

The results from lake and sea trials have demonstrated that the CVL produces an accurate measurement of the velocity vector, during a range of manoeuvres, including changing speed and direction, and at slow speed. The resulting position output agrees well with the GPS measurements of position.

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REFERENCES