PRECISION ACOUSTIC NAVIGATION FOR REMOTELY OPERATED VEHICLES (ROV)

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The ability to navigate a ROV to exact bottom locations or along a precise path is essential to many scientific and engineering tasks. Bottom and water column surveys along a precise and repeatable trajectory allow the monitoring of chemical and physical variables, and the study of sedimentation processes and biological phenomena. Precise navigation is also required for high-resolution synthetic sonar observations and for placement and retrieval of various devices on the bottom. This paper reviews principles behind acoustic navigation and provides a survey of commercially available Ultra-Short Baseline (USBL) navigation systems. A novel high precision navigation system is proposed that offers several advantages over the surveyed systems. Specifically, the precise position and trajectory of a ROV tethered by a cable to a bottom node is obtained using sensitive phase measurement of an acoustic signal. Proof of this concept through shallow-water and deep-water prototypes will be carried out shortly at the University of Victoria.

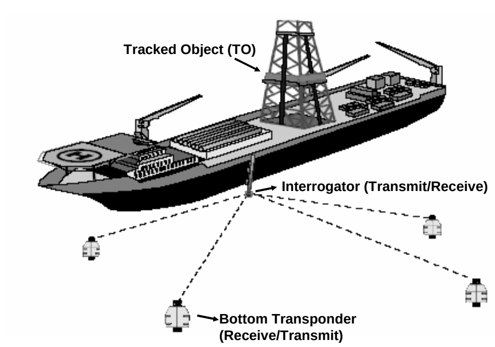
INTRODUCTION

Diverse data is collected during underwater ocean surveying by sensors placed on various platforms such as towed bodies, towed arrays, autonomous underwater vehicles (AUV), a ROV, and others. For the data gathered to be of value, the location from which it has been acquired must be accurately known. This can be accomplished by an acoustic navigation system that allows monitoring of the platform position. Acoustic navigation systems presently used include: long baseline (LBL), short baseline (SBL), and ultra-short baseline (USBL) [1-12]. These systems use transducer arrays as aids to navigation and positional tracking of an underwater object from onboard a vessel.

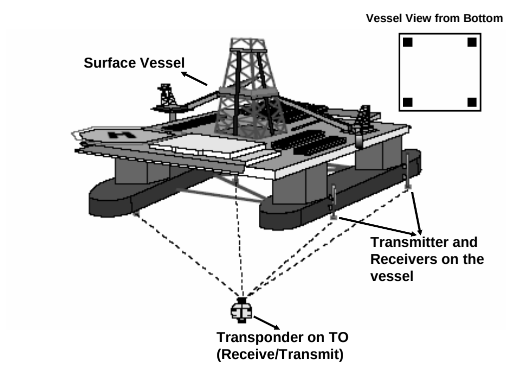
1. ACOUSTIC NAVIGATION SYSTEMS

Distance between transducers forming a receiving/transmitting array is generally used to define the type of a navigation system, as follows: LBL: 100m ~ 6,000mSBL: 20m ~ 50m
USBL: <10cm.

An LBL system uses transponders located on the seabed and a transducer (interrogator) mounted on the tracked object (TO). The TO can be a surface object (like a ship) or subsurface object (like a ROV). The bottom placed transponders are interrogated from the TO. Upon receiving an acoustic signal, the transponder transmits a reply, as illustrated in Figure 1(a) [3]. The travel times of the transmitted signal from the TO to the transponders and back are measured. Knowing the sound velocity c at the site allows these measurements be converted directly to slant distances and therefore the position of the TO can be calculated. Typically, three or more transponders are required to determine an object's position. This position is with respect to relative or absolute seafloor coordinates [3]. A LBL system can also work in a reverse manner; i.e., with the transponders located on the sea surface. Most LBL systems work at a frequency of approximately 10 kHz and provide position accuracy to within a few meters and a maximum range on the order of a few kilometers [1]. Generally LBL systems are expensive and difficult to deploy.



(a)



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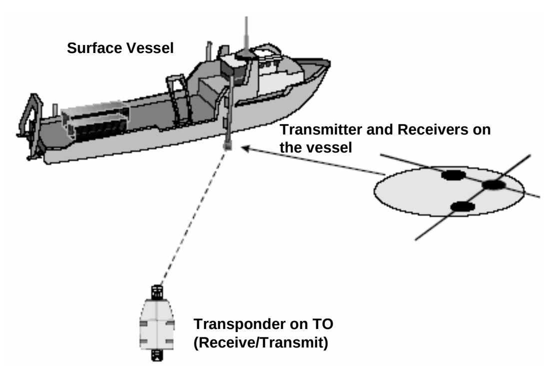

(c)

Fig.1 Acoustic Navigation Systems

SBL systems operate on a similar principle as LBL, but the receiving hydrophones are mounted at fixed locations on the vessel as illustrated in Figure 1(b). A signal is sent to a transponder attached to the underwater TO. Measuring time of arrivals provides the position of the object with respect to the vessel. Since the vessel is subject to pitch, roll and yaw movements, the calculated position of the underwater object has to be corrected using a vertical reference unit (VRU) and a heading reference unit (HRU) [3, 13].

The operating principle of USBL systems is similar to that of SBL systems except that the three (or more) receivers are all built into a single transponder assembly in close proximity (approximately 6 cm apart) as illustrated in Figure 1(c). Multiple receivers are used in order to determine the relative time of arrival (TOA) and direction of arrival (DOA) of the signal. The signal delays cause phase shifts between the received signals in each receiver. Usually, the incoming phase of the signal is measured relative to the baseline between two receivers in order to determine the acoustic phase angle θ_1 (azimuth angle) in the horizontal X-Y plane. If a third receiver is used, orthogonal to the first two, the acoustic elevation angle θ_2 between the X-Y plane and the vertical Z-axis can be determined [4].

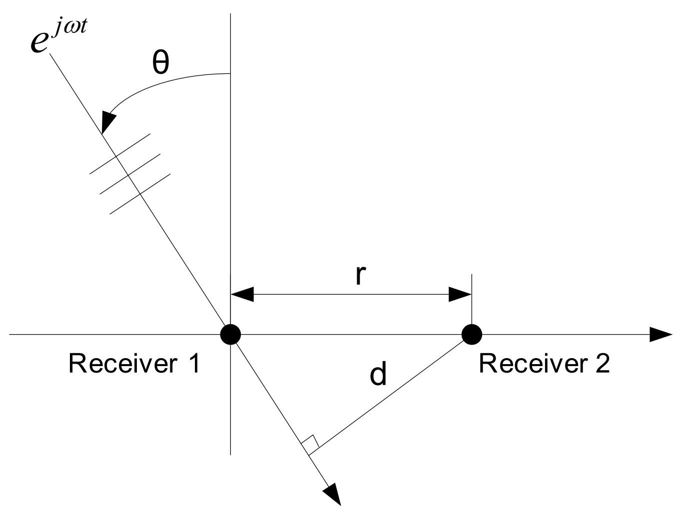

Fig.2 Phase Delay between Transducers

Phase differences are calculated using one of the receivers as a reference as shown in Figure 2. If the pressure at the centre of one receiver is assumed to be $e^{j\omega t}$ then at a distance r from the centre of the array the waveform is delayed by

$$\tau = d / c = r \sin\theta / c . \tag{1}$$

This delay causes a phase difference $\omega\tau$ between the signal at receiver 1 and receiver 2. Here θ is the signal's coming direction measured with respect to the array's broadside direction. If the azimuth angle θ_1 and elevation angle θ_2 are measured by using three receivers placed in a triangular configuration, we can calculate the three-dimensional position (x, y, z) of the object.

To work efficiently in a multi-path environment, most of the current USBL systems use spread spectrum technology. This makes it possible to transmit signals on many different frequencies, thereby reducing the effect of multi-path signals. The system performance depends on an accurate estimate of

TOA of the acoustic signals [13,14,15]. Since only one transponder assembly is needed for an USBL acoustic positioning system, such a system is easy to deploy.

Numerous investigations have been done on ROV/AUV navigation and positioning, including the TOA-DOA joint passive location algorithm [16], passive arm (PA) based algorithm for short-range position measurement [17], and multi-sensor data fusion techniques for AUV navigation [18]. A correlation method, phase difference techniques, a mosaic-based method, and a Kalman-filtering method are also being employed for ROV/AUV navigation [19-22]. Studies have been done on Doppler-based navigation for underwater robotic vehicles [23-24].

2. REVIEW OF EXISTING USBL SYSTEMS

Low system complexity, easy deployment, and accuracy make USBL an easy tool to use. Numerous companies manufacture USBL systems for underwater positioning. Here, we briefly examine and compare six of the leading manufacturers' USBL equipment. Table 1 lists these, compared on the basis of range, accuracy (angular and slant range), operating frequency, beam width, and depth rating for transponder.

As seen from Table 1, the best accuracy for slant range measurement is offered by the Sonardyne Fusion System at 0.1%, yielding a positional error of ±10 cm at 100 m distance. The instrument having the best angular accuracy is the Kongsberg Simrad HiPAP at 0.12^o.

Tab.1 USBL System Comparisons (for SNR = 20dB)

Manufacturer	**System**	**Range (m)**	**Accuracy Angular (deg)**	**Accuracy Slant Range**	**Operating Frequency (kHz)**	**Beam-width (deg)**	**Signal**	**Depth Rating for Trans-ponder (m)**
Kongsberg Simrad	HPR410	1500	2.86	5%	20~32	80	N/A	152
Kongsberg Simrad	HiPAP500	4000	0.12	<20cm	21~24.5	N/A	N/A	152
Nautronix	NasPOS USBL	4500	0.143	0.25%	N/A	N/A	SS ADS	61
Nautronix	ATSII	2000	0.143	0.25%	15~18	N/A	Chirp	61
ORE	LXT	N/A	0.5	1m	22~30	N/A	N/A	152
ORE	Track Point II	N/A	0.1@50dB SNR	0.5%@50 dBSNR	4.5~30	N/A	N/A	152
Sonardyne	Fusion	7000	0.0572	0.1%	18~36	180	S. Spectrum	100
Link Quest	1500HA	1500	0.25	0.2m	31~43.2	150	S. Spectrum	3000
Link Quest	5000HA	5000	0.25	0.4m	14.2~19.8	90	S. Spectrum	3000
Link Quest	10000HA	10^4	0.25	0.50%	7.5~12.5	90	S. Spectrum	3000
IXSEA	PAPS	4000	0.12	0.20%	20~30	N/A	MFSK Chirp	152
IXSEA	Posidonia	6000	0.171	0.30%	12~18	120	MFSK Chirp	152

3. USBL SYSTEM FOR A SPECIFIED SCENARIO

As a specified application, we concentrate on a local positioning and navigation system. The object being tracked is a ROV tethered to an observatory (node) fixed on the sea floor, moving within a circle around the node. Land-based operators can control and monitor instruments, video cameras, and the ROV in real time through a suitable communication cable connecting the node with the land. An underwater positioning system is needed to determine the precise position of the ROV with respect to the node.. If the node has known absolute coordinates, absolute referencing could be used for the measured ROV position. In the proposed scenario, the vehicle can navigate within a radius of 60 m to 100 m from the node at depth up to 2500 m.

The only company that makes an inverted USBL system with a transponder that operates at this depth is Link Quest, listed in Table 1. This leaves only three choices for a USBL system that will work at the depth of 2000 m: the Link Quest 1500iHA, 5000iHA and 10000iHA. The prices for these three systems are US $45,000, US $80,000, and US $100,000, respectively. The Link Quest 1500iHA (inverted) would be the best choice to implement this system. Its accuracy is ±20 cm (0.2% slant range at 100 m) and an angular accuracy of 0.25º.

Some deep-water transducers with higher positioning accuracies are still in development. The beam-width needs to be expanded to 360º for the system to track the ROV (or a crawler). This requires three transducers or a rotating head assembly, which will add extra cost for the systems. With these considerations in mind, we propose to develop a novel system for this application. It is expected to be inexpensive and to achieve the desired range/angular positioning accuracy in the specific scenario.

4. PROPOSED SOLUTION AND ITS INNOVATION

Most commercially available acoustic navigation systems are designed to operate from a surface platform and to track an object below. For reasons of versatility, those systems are autonomous in the sense that they do not take advantage of possible communication links over a tether cable connected to a ROV. In our specified scenario, we assume a ROV tethered to a bottom node with missions within approximately 100 m radius of the node as shown in Figure 3. The ROV mission will start from a fixed initial position (starting point). The ROV is equipped with a small omni-directional acoustic transmitter driven by a signal transmitted over the cable from a receiver located at the node. The acoustically transmitted signal is received by a receiving acoustic array located also at the node. In this arrangement, the transmitted signal is precisely known at the receiver and can be changed if needed. To illustrate the potential and simplicity of such an arrangement, let us consider a constant harmonic acoustic signal transmitted by the ROV. For such a short distance, a relatively high frequency carrier f can be applied. The bandwidth of such a signal at a node is determined only by the Doppler shift associated with a moving source. Let us assume as an illustration $f = 100$ kHz, corresponding to a wavelength of 1.5 cm in water. This means that for each change of radial distance between the ROV and the node equal to the wavelength, the phase difference between the transmitted and the received signals will change by 360°. If this phase is measured with a 10° accuracy, we can obtain the theoretical range resolution of 0.41 mm. Naturally, the received signal phase must be continuously monitored and integrated as the ROV moves.

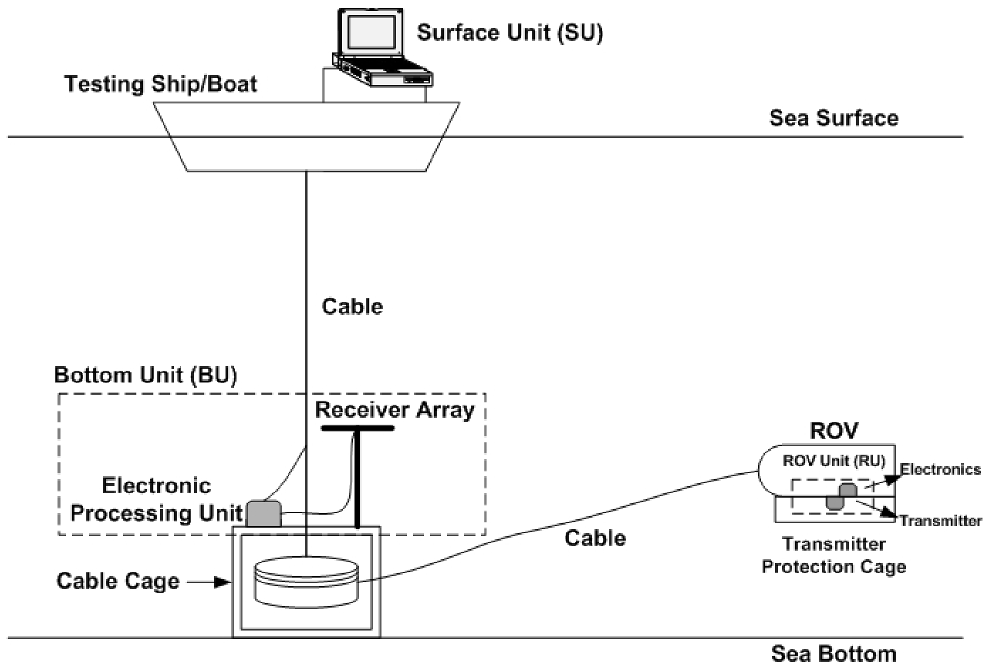

Fig.3 Proposed Navigation System for a Specified Scenario

This approach potentially offers significantly more spatial resolution and accuracy than the existing state-of-the-art for both USBL and LBL underwater navigation systems. These two types of systems differ in their approach to angle measurement but use the same method for range measurement. Both utilize a periodically transmitted short pulse that inherently limits range resolution and accuracy to no better than the pulse length (typically more than 10 wavelengths or 15 cm at 100 kHz). Resolution can be increased by shortening the transmitted pulse (or by using correlation techniques) and increasing the operating frequency. This, however, will result in bandwidth increase and, therefore, in a larger signal-to-noise ratio due to higher acoustic absorption losses and lower achievable transmit power at higher frequencies. Compounding the problem, the measurements can be made only at a rate dictated by the maximum range and the speed of sound (i.e., only one pulse can be in the water at any given time in order to avoid ambiguities). For a 100 m maximum range, the measurement rate for USBL or LBL systems is limited to less than 15 Hz and, since this is also typically the desired rate for ROV navigation updates (i.e., feedback to the operator), little room remains for averaging in order to improve the measurement accuracy. In the proposed approach, not only is the inherent accuracy much higher than existing systems, but the measurement is continuous because the method uses continuous signalling rather than periodic pulse transmissions. The phase fluctuations of the received signals are also due to transmission through water with variable refractive index. From a navigational point of view, this is a source of error (phase noise), but, at the same time, this phase noise can be used to monitor acoustic scintillation as an add-on feature useful for probing ocean currents and turbulence.

To measure ROV azimuth, an array of two receiving hydrophones separated by a distance much larger than the wavelength can be used. Again, the differential phase between these two signals can be used to track the azimuth angle. For example, for two hydrophones separated by

100 wavelengths (150 cm separation for f = 100 kHz), the differential phase between the received signals will change by 180° for only 2.3° change in azimuth ROV (from vertical to the array direction, i.e., from broad-beam direction). Assuming again a 10° signal phase resolution, a 0.06° azimuth resolution is achieved. As in the ranging case, this phase must be tracked and integrated. Once the ROV reaches its goal and rests on the bottom, its position is memorized for the next mission. From time to time, it might be necessary to reset the system by returning the ROV to its initial starting position.

The depth of the ROV can be monitored by precise pressure sensors located on the ROV and on the node location by using the pressure difference. Another, more likely, solution is an independent acoustic altimeter mounted on the ROV that will allow for its precise navigation above the bottom. It is also assumed that the ROV is equipped with a flux gate magnetic compass that will provide heading information.

5. RESEARCH OPPORTUNITY

In order for the proposed approach be practical, two fundamental issues must be addressed. The first is how to maintain accuracy if the system temporarily loses contact with the signalling source (signal fading); the second is how to assess system accuracy in the presence of multi-path (from bottom, surface and obstacles). Signal fading can occur, for example, if the line-of-sight between the ROV and the receiver is temporarily blocked by an object creating a shadow zone. The loss of signal means that phase measurements are not available for some period of time during which the vehicle is moving, so that when the signal is re-acquired the position may have changed by many wavelengths unregistered by the navigation system. Several approaches can be employed in order to maintain system accuracy during such signal loss. The simplest of these is an interpolation of the missing phase measurements during the time of the signal loss. This approach could incorporate external sensor inputs for vehicle velocity and heading or could directly utilize the rate of phase change before signal fading. A second approach is to increase the sophistication of the signalling waveform to include pseudo-random coding that would provide a periodic absolute time measurement (i.e., at the code rate) in addition to the phase measurements (i.e., still continuous). Yet another approach is to transmit more than one frequency continuously (but derived from the same reference clock in order to maintain phase relationship) and to use the relative phase pattern to resolve multiple wavelength ambiguities when they occur. Each of these approaches offers a mechanism for maintaining system accuracy during a temporary signalling loss.

The second issue is how to maintain system accuracy in the presence of multi-path. Multi-path has long been the nemesis of USBL and LBL navigation systems and is one of the primary reasons that pulsed transmission has been used in sub-sea navigation to date. This transmission is based on the expectation that multi-path arrivals are separated in time from the direct path and that multi-path signals arising from a previous transmission will decay before the direct path arrival of the next transmission. Unfortunately, both of these assumptions are not always satisfied, especially close to the seafloor or surface. Continuous transmissions are also subject to multi-path interference; however, in the near seafloor environment it is no worse than for pulsed systems. Newly developed angle-of-arrival signal processing methods for separating direct path and multi-path arrivals have been successfully demonstrated in underwater acoustic environments and are well suited to this application. Therefore, further study can be made for a detailed analysis of the multi-path problem and solutions that will maintain navigation accuracy in its presence.

Another problem that has to be addressed is receiver angular sensitivity as well as the Doppler shift associated with a transmitter on a moving ROV. These issues will be addressed by investigation of novel two or three-dimensional arrays and associated signal processing algorithms. For instance, a multi-element-ring receiving array can offer certain advantages because of its symmetry and presence of redundant elements. An important generalization can be made to allow this type of navigation for un-tethered vehicles such as AUV. This is, in principle, possible by having acoustic transmitting and receiving capabilities both at the node and on the AUV. For instance, the AUV transponder may receive an acoustic signal at one frequency and retransmit a signal that is phased with the received signal. In simplest form, it can receive a signal at frequency f and retransmit its second harmonic at frequency $2f$. An important generalization would be to consider navigating several ROV or AUV simultaneously. A more sophisticated signal design for this (and other) purposes such as spread spectrum will be investigated.

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