Autonomous Underwater Unmanned Vehicular Recovery System based on Low-Cost Inter-Aural Time Differentiation Passive Sonar

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Abstract—Sensing systems for AUVs are deeply researched but post mission deployment recovery systems for these vehicles are equally important. This paper presents a low-cost recovery system designed to provide post mission recovery location discovery capabilities to AUVs. The recovery system discussed relies on inter-aural time differentiation of sonar pulses received by the AUV from a sonar beacon.

I. INTRODUCTION

By eliminating the operator from the chain of operation Autonomous Underwater Vehicles (AUVs) have helped improve the overall efficiency of marine research and also operations in the ocean related industries. Unlike Remotely Operated Vehicles, AUVs do not need a tether cable; this ability coupled with their autonomy provides them a much higher level of fault tolerance, the ability to perform more complex tasks and a much greater range for missions as well.

Though many post mission AUV recovery mechanisms based on acoustic localization systems exist, some of these commercial, [1] the cost and complexity render their use near impossible for low-cost missions and implementation in economical submersible vehicles.

As part of Indian Underwater Robotics Society’s (IURS’) goal to develop a low cost lightweight modular mission adaptable AUV, significant efforts were also put in to designing a portable and economically viable system for post mission recovery of the vehicle. The designed system utilizes acoustic sonar beacons; the signal transmitted by which is processed by the AUV’s on board passive sonar array utilizing inter-aural time differentiation to determine headings that would place the AUV within about 5 feet of the beacon for successful recovery. Following this very overall model of operation, the research team designed two methods for processing the received sonar pulses; one method utilizes digital logic in order to process the signal whereas the other is an analog wave differentiation method.

This paper discusses both these methods of sonar signal processing devised in order to aid the AUV in locating its surface zone; it also focuses on describing how inter-aural time differentiation can be implemented into a robotic acoustic tracking system to enable the robot to localize and orient towards the sound source. It also describes how the overall recovery system functions and then goes on to provide data on the testing of this system. The paper also presents some drawbacks that the recovery system currently possesses and the methods that are planned to improve performance of the system.

II. PASSIVE SONAR ARRAY

The artificial intelligence world of today demands effective communication between all electronic devices. For better communication robots have to become more sociable [2, 3]. It is therefore evident that acoustics plays a very important role in unmanned underwater robotic systems as well.

In the real world we use our hearing that gives us a full 360-degree “field of view” [4]. This helps us to localize things that are not in our field of vision, which may be obscured or hidden by another object [5]. Limited visibility, poor light conditions, variability of image quality, visual artifacts induced by moving artificial sources, objects lacking regular structure and form due to refraction, etc [6] cause optical systems, which we rely on heavily for terrestrial localization, to become ineffective underwater [7], thereby making acoustic systems the primary source for localization systems below the water’s surface [1].

A. Array configuration

As far as underwater acoustics is concerned, there are two main kinds of acoustic setups; stationary mono/multi-hydrophone configurations that are used to control selected areas and towed/on-board hydrophone arrays to continuously detect sound during navigation [8].

The system developed by IURS utilizes an on-board passive sonar hydrophone array configuration with individual transceivers placed in an Ultra-short, or Super-short, Baseline System (USBL or SSBL) to continuously detect and localize the acoustic beacons utilized to mark the recovery zone for the vehicle.

A USBL system measures phase comparison on an arriving “ping”, from the sonar beacon, between individual elements within the hydrophone array. This coupled with a time of flight interrogation technique provides a range to the beacon as well. Low system complexity and good range accuracy with time of flight systems [1] makes a USBL arrangement of the hydrophones in this low-cost recovery system the perfect choice. Furthermore, being a shallow to medium depth water solution, USBL is also an excellent choice because the accuracy of USBL acoustic systems is quoted as a percentage of slant range [4]; therefore, the greater the...
depth, the lesser its accuracy – in other words, USBL is appropriate for medium to shallow waters.

A pair of hydrophones spaced a maximum of ½ wavelengths apart to the center frequency of the incoming signal is mounted on the starboard and port sides of the AUV in order to provide the most efficient configuration. The only disadvantage of using two hydrophones is the ambiguity in the direction of the pinger, i.e. whether it is located towards the bow of the vehicle or the stern. This ambiguity can be overcome by spinning at a particular point to take multiple samples of the sound generated by the pinger.

B. Frequency Band & Hydrophones

Choosing the appropriate frequency band for the operation of the recovery system depends on a great many factors, primary being the area and depth to be covered by the submersible vehicle during the course of the mission.

Additionally, it is extremely important to take into consideration the various types of acoustic noise that the system encounters. While ambient noise is limited to the LF range (please refer to Table I), the noise generated by an unmanned system’s propulsion system generally peaks only up to about 1 kHz followed by a decrease. Reverberation, which arises as a direct consequence of using an acoustic localization system, has the following classifications [1]:

- Volume reverberation – scattering off the surface matter.
- Sea surface reverberation – scattering off the surface.
- Sea bottom reverberation – scattering off bottom layers and ocean bottom.

Since the time difference of arrival of the sonar pulse needs to be continuously monitored between the two transceivers, the accuracy of the sonar system depends greatly on the output of the hydrophones. As such, taking into account all the afore discussed issues, the MF band was chosen for operating the system designed by IURS in order to provide the best possible accuracy over a medium to long range operating distance with the least possible effect of ambient noise and reverberation as well (please also refer to Table II).

To this effect the test system was equipped with Aquarian Audio hydrophones with frequency response between 10 Hz to 50 kHz and an omni-directional polar response. These hydrophones were also chosen because of their low cost to performance ratio.

C. Preamplifyng Band Pass Filter & Comparator

Since the model of the hydrophones being used does not contain built-in preamplifiers, the raw signal obtained contains all the undesired ambient noise and frequencies and additionally the voltage is also not high enough for further processing of the signal. As such, the preamplifier assists in amplifying the voltage to a suitable level for filtering, rejects common noise and provides a wide bandwidth for effective processing of the signal.

The filtered and amplified signal from the preamps is passed through an active band pass filter with calculated variable resistors and capacitor values enabling us to choose any frequency between 20 kHz to 30 kHz with a bandwidth which can go as low as 1 kHz to a maximum of 10 kHz, once again in order to provide the best possible accuracy and range of operation.

This system also comprises of comparators that actually compare the amplitude voltage with a threshold that is set experimentally in order to ensure that the autonomous unmanned submersible is within the pre-defined recovery zone diameter locale of the sonar beacon that is used to localize the recovery point for the AUV.

**TABLE I.**

<table>
<thead>
<tr>
<th>Freq. Type</th>
<th>Freq. Range</th>
<th>Max Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Frequency (LF)</td>
<td>8 kHz – 16 kHz</td>
<td>&gt;10km</td>
</tr>
<tr>
<td>Medium Frequency (MF)</td>
<td>18 kHz – 36 kHz</td>
<td>2km – 3km</td>
</tr>
<tr>
<td>High Frequency (HF)</td>
<td>30 kHz – 60 kHz</td>
<td>1500m</td>
</tr>
<tr>
<td>Extra High Frequency (EHF)</td>
<td>50 kHz – 110 kHz</td>
<td>&lt;1000m</td>
</tr>
<tr>
<td>Very High Frequency (VHF)</td>
<td>200 kHz – 300 kHz</td>
<td>&lt;100m</td>
</tr>
</tbody>
</table>

*This assumes band noise at the transceiver to be less than 95 dB and the source beacon to be >195 dB.*
III. SIGNAL PROCESSING

To surface exactly at the source of sound within the environment we need to calculate the bearing angle, azimuth, with respect to the AUV; azimuth represents the angle at which the sound source is located with respect to the AUV [4]. We achieve this by calculating the time difference of arrival (TDOA) of the wave front at the two hydrophones.

This is an analogy to Interaural Time Difference (ITD) Cue used in the auditory cortex of the mammalian brain [9, 10]. The ITD in Sonar Localization is the time taken by the sound to arrive at the contralateral hydrophone once the ipsilateral hydrophone has detected the sound. When the first hydrophone detects the ping we need to calculate the TDOA from the same point along the waveform in order to get the accurate measure of the ITD and thereby the appropriate heading for the recovery zone sonar pinger.

Any effective sonar system relies heavily upon its signal processing in order to derive accurate results. So as to achieve this aim and develop inexpensive high-speed signal processing techniques to locate the sonar beacon, two separate methodologies were devised.

A. Digital Logic Circuit

In order to locate the pinger we developed a custom logic circuit, shown in Figure 2, to process the sonar signal. Taking in the signals received by the two hydrophones, named H1 and H2, it is passed through the logic circuit that at the end points provides us two signals that assist in determining the FPA and the TDOA, which are together used to calculate the heading towards the sonar pinger.

By utilizing the truth table, shown in Table III, the FPA is determined. Logic high on FPA would mean that the first point of arrival was on H2. Logic high on this source along with a high on TDOA would enable us to calculate the time difference between the two waves and also tell us that the FPA was on H2. Similarly when we the logic pin H1 goes high, TDOA is high which gives us the difference and FPA goes low, which implies that the arrival was on H1. As obvious when both H1 and H2 are high simultaneously the difference is nil implying that the source is directly in front of the AUV and equidistant to the hydrophones. TDOA, as shown in Figure 1, provides us with a PWM signal that is toggled high proportional to the time difference of arrival of the first pings between each hydrophone, H1 and H2.

Since we know the speed of sound in water, the distance to the sonar beacon in the recovery zone can also be calculated. Referring to Figure 3, assuming that the sonar pinger is located at point S and the robot is between points H1 and H2, with H1 and H2 being the two hydrophones that are placed in a baseline configuration, then the angle that the AUV needs to modify its heading by is the angle theta.

The angle theta is computed by calculating the TDOA of the sound pulses from S at H1 and H2. In order to calculate this value, it can further be assumed that the time difference between each pulse emitted by S is X seconds and that the pulse lasts for Y seconds furthermore, let T1 be the time difference between the time of arrival of the first pulse and the subsequent second pulse on the hydrophone H1. Similarly, T2 can also be calculated for the hydrophone H2. Furthermore, If T1 > T2 then the robot turns towards H2 or vice-versa. If the distance between S-H1 is a, H1-H2 is b and S-H2 is c then these values can be computed easily using the formula s = v * t, where $t = TDOA_{H_{1,2}} - (X + Y)$ and v is the velocity of sound in water.

B. Analog wave differentiation

The second signal processing method calculates the difference between the phases of the waves received at the hydrophones, H1 and H2. Since this method primarily relies upon analog electronics it is termed as the analog wave differentiation method.

The waves received at the two hydrophones, H1 and H2, are phase shifted because the distance the wave has to

![Figure 1. Preamplifying Band Pass Filter Schematic.](image)

![Figure 2. Digital logic circuit to determine the First Point of Arrival (FPA) of the ping and the Time Difference of Arrival (TDOA) of the ping between the two hydrophones.](image)

![Figure 3. Conceptual representation of AUV, hydrophones and a sonar pinger.](image)

<table>
<thead>
<tr>
<th>H1</th>
<th>H2</th>
<th>TDOA</th>
<th>FPA</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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TABLE III. TRUTH TABLE FOR DIGITAL CIRCUIT IN FIGURE 1
travel in order to reach the two hydrophones will not be exactly the same while the AUV is acquiring headings. As such, the waves received from the sonar pinger at the two hydrophones resemble the AC waves depicted in Figure 4.

In order to calculate the TDOA, FPA and time of flight of the sonar signal these AC waves are first converted to their corresponding square waves using a Schmidt Trigger based circuit. This transformation of the AC waves is depicted in Figure 5; the dark black shaded areas on the two axes are the crests of the square waves, while the light grey shaded area depicts the time difference of arrival, or TDOA, of the sonar pings between the two hydrophones; the dark grey area on the other hand depicts the time it takes for the ping to complete on the second hydrophone after the signal has already subsided on the first hydrophone. Now, by subtracting the two square waves a third wave, shown in Figure 6, which corresponds to the light and dark grey shaded areas, is obtained. This newly obtained wave now contains all the information necessary to deduce the FPA, calculate the TDOA and also the distance to the sonar beacon in the recovery zone.

Following the same symbols as defined in the previous section and referring to Figure 6, if the resultant square wave is in the negative spectrum, the FPA is computed to be H2, whereas if the vice-versa were the case then the FPA would be H1. Furthermore, the length in time of the light grey crest from the resultant square wave provides the TDOA as well. Using the method described in the previous section, since the TDOA is known, theta may now be calculated in order to obtain the angle by which the AUV must modify its angle to have an accurate heading towards the retrieval zone.

Since the obtained wave also provides the ability to calculate the total time of flight between the first and second pings, the distance to the acoustic pinger is easily calculable by the formula \( s = v \times t \).

If \( T \_x \) is the time when the first dark grey pulse starts and \( T \_y \) represents the time when the second light grey pulse starts, then \( t = (T \_y - T \_x) - (X + Y) \).

A low-cost lightweight AUV name Jal, designed by IURS, was used as the testing bed for this recovery system; both methods of signal processing were used while testing the recovery system. This AUV was equipped with self manufactured PCBs of the Preamplifying Band Pass Filter and Aquarian Audio H1 hydrophones. An Atmel ATmega16 AVR microcontroller was used as the primary sonar-processing interface of the AUV and the software for the same was developed utilizing Bascom in order to provide rapid prototype development. The MFP-1 Sonar Pinger from JW Fisher’s was used to test the recovery system with pinging frequencies between 24 kHz and 30 kHz, a gap of 2 seconds between each individual ping and the ping lasting for 0.2 seconds.

While the Digital Logic Circuit processing technique was employed two inputs of the ATmega16 were dedicated to timing the length of the strobe and determining which hydrophone the signal arrived on first utilizing software based on the previously discussed truth table.

The Analog Wave Differentiation method used the interrupts on the ATmega16 to start and stop counters in order to deduce the FPA, TDOA and enable the software to calculate the distance to the pinger.

The tests were carried out in a swimming pool with an average depth of about 6 feet and approximate dimensions of 35 feet length and 15 feet width.

The AUV was able to find the recovery zone of a 5 feet diameter around the pinger with high degree accuracy during the tests; the tolerance range for errors was 2-3 feet off the recovery zone and the success rate was approximately 70% surfaces within the recovery zone. Similar results were obtained across the entire range of operating frequencies of 24 kHz to 30 kHz (with changes in steps of 1 kHz) and no significant differences were observed while testing the two separate algorithms.

Though the 70% accuracy of the algorithm is a good beginning for the recovery system a few improvements can definitely be applied in order to improve the accuracy and speed of the system. Inclusion of additional hydrophones will remove the necessity of the AUV to spin on its axis in order to locate the directional heading of the sonar beacon, thereby greatly improving the performance of the system in terms of speed. Additionally, a sound digital signal processing (DSP) system will add to the
accuracy and efficiency of the system as well. These improvements are planned for future iterations of this system and further research is also being conducted in order to make as many improvements as possible while maintaining the low-cost aspect of this recovery system.

VI. CONCLUSIONS

Though there are a few other recovery systems for AUVs the system presented in this paper provides a low-cost AUV recovery system with relatively high accuracy, making it a viable option for shallow water missions. The choice of the signal processing methodologies provides a balance between complexity of deployment and performance making implementation of the system in a wide array of unmanned systems possible. With some further improvements this system will provide a low-cost highly accurate and efficient alternative to the existing recovery systems.

REFERENCES


