Simulating Underwater Acoustic Communications in a High Fidelity Robotics Simulator

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Abstract
The maximum potential for underwater exploration rests within the use of multiple Autonomous Underwater Vehicles (AUVs) and tasks involving human diver-AUV coordination. Such missions are gaining increasing popularity with the advent of better control mechanisms and availability of acoustic modems. However, high costs and the lack of useful tools to simulate multi-AUV tasks have hindered the full potential of the field. Though simulators could aid the development of AUV communication systems to help such missions, the few existing simulators focus upon simulating a single vehicle and, as such, do not provide tools for simulating underwater communication systems. In this paper we present an overview on modeling of the underwater acoustic channel, taking into account the high degree of local variability of ocean conditions, multi-path echoes and ambient noise, within the framework of an underwater acoustic communications server for the Unified System for Automation and Robotics Simulator (USARSim) robotics simulator, a simulation tool is capable of modeling multi-robot missions with high accuracy.

1. INTRODUCTION
Off-shore research and exploration has seen an increased use of Autonomous Underwater Vehicles (AUVs) in the last few years. As in the terrestrial and aerial robotics fields, using multiple AUVs to perform coordinated tasks or deploy AUVs in diver coordinated missions holds the maximum potential for the growing use of AUVs. However, the high cost of conducting off-shore missions has led to limited testing time for design and development of the cooperation algorithms and systems, thereby reducing the full potential of such systems. From fabrication to deployment the costs associated with multiple AUVs deployed in a network can be quite high. Coordination and control of multiple AUVs requires dependable wireless communications between each vehicle. Since the radio channel does not function underwater and the optical channel has very limited transmission range Akyildiz et al. (2004), most wireless underwater communications between AUVs are implemented using the underwater acoustic channel. The costs of a dependable underwater acoustic modem too are in the order of several thousand dollars and off-shore deployment and recovery of underwater vehicles from a small boat can be in thousands per day Partan et al. (2006). Such high costs associated with off-shore testing can be a bane to development in case revisions are necessary.

Though these acoustic networks enable the use of wireless networks in a host of applications for the underwater environment, the acoustic channel access method also poses some very important challenges to achieving near real-time communications in the form of limited bandwidth-capacity, low battery power availability with none to little possibility of recharging and the high likelihood of network disruptions Sozer et al. (2000). Issues such as long and varying propagation delays, multi-path echoes and high and varying ambient noise make the acoustic communication design process highly error-prone, and as such, must also be taken into consideration during the design of any underwater acoustic communication system.

Channel complexity and the high costs associated with off-shore deployment and testing highlight the need for a simulator that can accurately model the effects of the underwater environment on AUVs and the effects of the volatile underwater acoustic communication channel used to implement the coordination and control data exchange. Though there are plenty of robotics simulators available Craighead et al. (2007), not much work has gone into simulating the underwater environment in the popular robotics simulators Craighead et al. (2007). Furthermore, the effort in simulating network communication between AUVs has also been severely lacking Bielohlawek (2006), thereby forcing system designers to depend upon off-shore testing for dependable results. The Unified System for Automation and Robotics Simulator (USARSim) environment is quite popular with the rescue robotics community due to its strong physics engine and the ability to easily create models of new environments and robots. The extensibility of USARSim combined with its proven capabilities in simulating multi-robot cooperative tasks makes it an ideal simulation environment. As a result of its physics engine base, and model import capabilities, USARSim already has the ability to model the underwater environment and simple marine vehicles. However, the ocean being a highly complex medium for the propagation of sound, due to inhomogeneities and random fluctuations, including
effects of the rough seas and ocean bottom variances, it is necessary to build extensions that would provide feedback on acoustic communications. The Wireless Simulation Server (WSS) underwater acoustic communications plugin for USARSim was designed for this purpose.

The following sections provide an insight on acoustic propagation models which were developed along with information on the channel characterization approach that was used for the simulator. This is followed by an overview on the USARSim robotics simulator and the extensions we made to it in order to enable simulations of mobile underwater vehicles. A discussion on the extensions to WSS for enabling underwater simulations and also some results based on our test cases is followed by conclusions.

2. ACOUSTIC PROPAGATION MODEL

Even though wireless connectivity is achievable underwater by using the acoustic medium, the acoustic channel is considerably different from the commonly used radio channel Stojanovic (2006). In this section we present the different aspects of the underwater acoustic channel as they were used in our simulation model.

2.1 Propagation Delay

For most purposes the speed of sound in water is taken to be approximately 1500 m/s. While this is accurate within a certain range, the underwater channel is a complex environment which is affected by many varying factors, primarily temperature, salinity and depth. Furthermore each of these factors may also be interdependent or varying across the ocean. It is, as such, important to have an accurate model of the effects of these parameters on the speed of sound in water.

The speed of sound in water has been a focus of analysis by many mathematical models. We chose to utilize the expression proposed by the authors of MacKenzie (1981) since it calculates the speed of sound in water with an error in the speed estimate in the range of approximately 0.070 m/s:

\[ v = 1448.96 + 4.591C - 5.304 \cdot 10^{-4}C^3 + 1.340(S - 35) + 1.630 \cdot 10^{-2}D + 1.675 \cdot 10^{-7}D^2 - 1.025 \cdot 10^{-2}C(S - 35) - 7.139 \cdot 10^{-13}CD^3 \]  

(1)

where \( v \) is the sound velocity in m/s, \( C \) is the temperature in degrees celsius, \( S \) is the salinity in parts per trillion (ppt) and \( D \) is the depth in meters.

Since the speed of sound can vary greatly in regions of thermocline and halocline, and most AUV missions operate within these regions Caiti et al. (2009), determining speed of sound accurately is crucial.

2.2 Propagation Loss

Propagation loss is composed mainly of three aspects, namely, geometrical spreading, attenuation by absorption and the anomaly of propagation. The latter is nearly impossible to model and as such the attenuation, in dB, that occurs over a transmission range \( l \) for a signal frequency \( f \) can be obtained by:

\[ 10\log A(l, f) = k \cdot 10\log l + l \cdot \alpha \]  

(2)

where \( \alpha \) is the absorption coefficient in dB/km and \( k \) represents the geometrical spreading factor. Geometrical spreading loss can be widely categorized as spherical or cylindrical. Cylindrical spreading occurs when the transmitter and receiver are located a short distance, while spherical spreading is pronounced in long range communications. The geometrical spreading factor can be substituted with values shown in Table 1 in order to represent the type of spreading that occurs.

2.3 Absorption Coefficient

Attenuation by absorption occurs due to the conversion of acoustic energy within sea-water into heat. This process of attenuation is frequency dependent since at higher frequencies more energy is absorbed. There are several equations describing the processes of acoustic absorption in seawater which have laid the foundation for current knowledge.

Table 1. Values for representing types of geometrical spreading via the geometrical spreading coefficient \( k \)

<table>
<thead>
<tr>
<th></th>
<th>Spherical</th>
<th>Cylindrical</th>
<th>Practical</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The attenuation by absorption is dependent upon the ambient conditions, transmission frequency and distance, and as such, the Fisher & Simmons model proposed in Fisher and Simmons (1977) is used for the modeling work presented here. This model also takes into account the effects of relaxation frequencies caused by the presence of boric acid and magnesium sulphate in the ocean.

In Equation 3 \( A_1 \), \( A_2 \) and \( A_3 \) represent the effects of temperature on signal absorption, while \( P_1 \), \( P_2 \) and \( P_3 \) represent the effects of depth and \( f_1 \) and \( f_2 \) represent the relaxation frequencies introduced due to the absorption caused by the presence of boric acid and magnesium sulphate in oceanic water. These coefficients may be obtained from Table 2.

\[ \alpha = A_1P_1f_1^2 + A_2P_2f_2^2 + A_3P_3f_2^2 \]  

(3)
Table 3. Formulae Providing PSD of the Ambi- 
et Noise

\[
\begin{align*}
10 \log N_i(f) &= 17 - 30 \log f \\
10 \log N_s(f) &= 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03) \\
10 \log N_w(f) &= 50 + 7.5w^2 + 20 \log f - 40 \log(f + 0.4) \\
10 \log N_{th}(f) &= -15 + 20 \log f
\end{align*}
\]

2.4 Ambient Noise Model

Ambient noise in the ocean can be described as Gaussian and having a continuous power spectral density (PSD). The four most prominent sources for ambient noise are the turbulence, shipping, wind driven waves and thermal noise. The PSD in dB re \( \mu \text{Pa per Hz} \) for each of these is given by the formulae Urick (1983) shown in Table 3.

The ambient noise in the ocean is colored and hence different factors have pronounced effects in specific frequency ranges. In the noise model equations we utilize, this colored effect of noise is represented by \( N_i \) as the turbulence noise, \( N_s \) as the shipping noise, \( N_w \) as the shipping factor lies between 0 and 1, \( N_w \) as the wind driven wave noise (w as the wind speed in \( m/s \)) and \( N_{th} \) as the thermal noise. The overall ambient noise PSD may be obtained from:

\[
N(f) = N_i(f) + N_s(f) + N_w(f) + N_{th}(f)
\]

3. CHANNEL CHARACTERIZATION MODEL

For the purpose of simulation the performance of the underwater acoustic channel can be characterized by received signal power, signal-to-noise ratio (SNR) and the capacity. We utilize the equations presented by the authors of Stojanovic (2006); Sehgal et al. (2009) in order to perform the channel characterization in our simulator.

3.1 Received Signal Power

If a signal with frequency \( f \) is transmitted over distance \( l \) with a power \( P_{tx} \), then we can calculate the arriving signal power \( P_{rx} \) in dB:

\[
10 \log P_{rx} = 10 \log P_{tx} - 10 \log A(l, f)
\]

The result obtained from Equation 5 takes only the case for directional transmission in to account, i.e., the most direct propagation path from transmitter to receiver. However, in case of a transmission that is not directional to be modeled, this equation can be extended for the indirect routes as well.

3.2 Signal-to-noise Ratio

The signal-to-noise ratio (SNR) of an emitted underwater acoustic signal at the receiver can be expressed by the passive sonar equation Urick (1983):

\[
\text{SNR} = \text{SL} - \text{TL} - \text{NL} + \text{DI}
\]

Here, \( \text{SL} \) is the source level, \( \text{TL} \) is the transmission loss, \( \text{NL} \) is the noise level and \( \text{DI} \) is the directivity index. The path loss represented by Equation 2 is the transmission loss \( \text{TL} \). The noise level \( \text{NL} \) may easily be obtained from Equation 4, leading to the rewriting of the passive sonar equation for obtaining the SNR, when a particular transmission frequency \( f \) is used over a certain distance \( l \), in dB:

\[
10 \log SNR(l, f) = 10 \log P_{tx} - 10 \log A(l, f) - 10 \log N(f)
\]

Rewriting Equation 7 can be useful in determining the transmission power necessary in order to maintain a minimal SNR for a certain transmission distance and frequency at a particular depth and ambient oceanic conditions.

3.3 Bandwidth and Channel Capacity

Most current reported results focus on the channel capacity calculations that do not take into account the effect of parameters based on the ambient ocean environment and network deployment topology. The authors of Kwon and Birdshall (1986) use a channel model with additive Gaussian noise and in Leinhos (1996) the work focuses on using a Rayleigh fading model along with additive white Gaussian noise. The work described in Stojanovic (2006); Harris and Zorzi (2007) establishes the relationship between capacity and distance, while the authors of Sehgal et al. (2009) show the dependence of capacity on depth and temperature as well.

As such, in order to account for the dependency of capacity on transmission frequency and distance, depth and temperature, we utilize equations proposed by Sehgal et al. (2009). Bandwidth, \( B \), is dictated by the modern choice. We utilize the Shannon theorem to determine the maximum capacity bound and by extrapolating from Equation 7 we obtain the channel capacity, \( C \), over a transmitted distance \( l \), \( C(l) \) by:

\[
C(l) = \int \log_2 \left( 1 + \frac{P_{tx}}{A(l, f)N(f)B} \right) df
\]

4. USARSIM AND UNDERWATER SIMULATIONS

USARSim is a high-fidelity simulation tool for simulating robots and environments based on the Unreal Tournament game engine. USARSim is the basis for important current-day robotic simulations, the most famous being represented by the RoboCup rescue virtual robot competition. USARSim provides superior visual rendering and physical modeling due to an underlying physics engine. This enables the entire effort to be devoted to the robotics-specific tasks of modeling platforms, control systems, sensors, interface tools and environments. Advanced editing features for almost every aspect of the simulation, with a special focus on robots and environments, further adds to the advantages of USARSim.

All these advantages and its modular nature in developing new additions for sensors, modules and ability to model complex underwater environments on the strengths of a proven physics engine makes it a suitable tool to model the multi-AUV underwater acoustic communications in as well. In this section we provide some details on the underwater environmental and submersible vehicle modeling capabilities of USARSim along with information on WSS and the extensions we made to both these tools in order to enable mobile multi-AUV communication simulations.
4.1 Underwater Environments

Figure 1. Screenshot of the USARSim default model and submarine

In order to correctly evaluate the communication model and test the effects of algorithms, methods and control schemes it is important to have environment and robot models that mimic reality. USARSim has a model world simulating an underwater environment available by default, but others can also be easily created using the Unreal Tournament model editor. We used the default model containing water as our testing world model.

4.2 Vehicle Model

Though any vehicle models can be created and imported into the USARSim environment, we chose to use the Submarine model which is provided by default. This model can have sonar sensors, imaging sensors, echosounders, side scan and an optical camera simulated on it. The default implementation of the library to interface with USARSim did not have an implementation of a driving mechanism for the submarine and as such we implemented a drive mechanism for the propeller, rudder and stern planes, thereby providing us full mobility control of the submarine and giving us access to testing mobile-AUV communications.

4.3 Wireless Simulation Server

WSS is an USARSim plugin that enables simulation of 802.11x wireless network links. WSS works using plugins to implement propagation models allowing for further extensibility. The signal degradation is calculated based upon parameters that are setup for the propagation model plugin and it governs whether connection between robots is possible or not.

Figure 3. Screenshot of the propagation model configuration window

Our channel model was implemented as a propagation model plugin for WSS. The model configuration dialog in Figure 3 shows how the user can configure the ambient noise parameters to suit the real environment being modeled. Since USARSim does not have a way to provide the depth of the robot to WSS, a sea level function was implemented. This defines the sea level in the world map so that the robot’s depth could be calculated using its cartesian coordinates. The determined depth is used to obtain the temperature from the global thermocline average to compute the propagation delay and attenuation coefficient.

The user can also specify the signal transmission strength, cutoff strength, bandwidth and center frequency to model any modem without making changes to WSS or USARSim. WSS by default only supports robots being able to retrieve signal strength for the target robot. This is inadequate for the underwater networking scenario where the ability to retrieve propagation delay and channel capacity is also important. As such, we extended WSS to support the following functions:

- GETPD returns the propagation delay between the querying robot and the target robot specified in the query string.
- GETBW returns the channel capacity in kbps between the querying robot and the target robot specified in the query string.

The environmental modeling ability of USARSim gives the capability of also modeling and obtaining a bottom profile of the ocean floor. This is helpful since the bottom of the ocean is a great contributor to signal interference as a result of reflections that occur from the seabed in shallow water acoustic communications. The bottom profile can have a significant effect upon multi-path propagation.
Figure 4. Multi-path signal propagation in the underwater environment and the use of ray-traces in USARSim & WSS to retrieve their signal strength at receiver to obtain multi-path interference likelihood.

interference as well. As such, it is important to be able to test the likelihood of interference due to bottom reflections with the transmission signal. WSS was extended to retrieve bottom multi-path signal interference through the following function:

- GETML returns the interference likelihood as 0 or 1 for a distance to the surface bottom provided in the query string.

Figure 4, the depth of the bottom at multiple points, in this case A, B and C, across the direct transmission line between the transmitter and receiver is obtained. Another ray trace between the transmitter, each of the bottom points and receiver is performed in order to obtain the path that a multi-path echo scattered transmitted signal would take, represented by the red lines in Figure 4. The total distance travelled by a reflected wave, from transmitter to bottom and then to receiver, is obtained. This distance for each individual wave is used to determine the arriving signal strength on a particular path by using the channel characterization equations. In case, the PSD of any of the sampled paths is higher than the minimum required reception strength, as determined by the modem properties, multi-path signal interference is determined to be likely.

Though only three points along the direct path are considered in Figure 4, this is only for example. The actual simulator implementation takes the number of points across the direct propagation path to be considered as an input variable set by the GETML command.

WSS performs the channel characterization in real-time, as the simulation is executed within USARSim and provides feedback to the querying robots. This realtime calculation allows the simulation to take in to account any changes that may occur in the environment or any actions the submersible vehicle might be taking at the time.

5. SIMULATION RESULTS

The USARSim simulator provides a familiar environment to develop and perform multi-AUV simulations in. However, before the results of a simulator can be considered dependable, they must be validated. As such, this section provides an overview on the results obtained from the simulator and compares them to previously reported results.

In order to predict the accuracy of the propagation delay calculated by the simulator an experiment similar to the one run by Harris et al. (2007) was executed with two nodes, both situated 1 km apart. The depth of both these nodes was progressively increased while maintaining the same depth for both the nodes and keeping the 1 km distance between them constant. A comparison between the results obtained and previously published literature made it evident that USARSim WSS results mimic those previously reported.

Figure 5. The arriving signal strength while the distance between the transmitting and receiving nodes was varied between 4 to 180 m and the transmit power was also changed.

The arriving signal strength is very useful in determining the quality of the arriving signal. The evaluation of the arriving signal strength is not a straightforward comparison like other values since it is dependent upon the transmission strength necessary to achieve a desired SNR. As such, in order to test the accuracy of the simulator, it is important to draw a few inferences available data.

It is known that available capacity drops with distance and to achieve a higher capacity higher transmission power is necessary Sehgal et al. (2009) . Conversely, available capacity is proportional to the transmission power utilized. As such, we can deduce that the signal strength should reduce with distance in a somewhat logarithmic fashion.

Keeping this in mind an experiment while keeping a depth of 100 m constant, using the standard thermocline and varying the distance between the two nodes between 4 m and 180 m and also changing the transmission power between 60 dB and 120 dB, was executed in the USARSim WSS environment. The results of this experiment can be seen in Figure 5. Since the shape of this figure follows the expected shape, it can be deduced that the simulator works accurately.
Figure 6. The channel capacity while the distance between the transmitting and receiving nodes was varied between 4 to 180 m and the transmit power is also changed.

Using the same experiment as the one which provided results for received signal power, the values of channel capacity were also obtained and plotted in Figure 6.

Figure 7. The bandwidth and capacity while the distance between the transmitting and receiving nodes was varied during the study conducted by Stojanovic et al. [6] (Upper line is capacity).

It is clear from Figure 6 that the capacity reduces with distance between the nodes and increases with increased transmission power. Upon comparing obtained results to Stojanovic et al.'s Stojanovic (2006), depicted in Figure 7, it is clear that the shape of the curves is very similar irrespective of the transmission frequency and power utilized. The similarity in the shape of the curves argues in the favor of the overall robustness of results provided by the simulators.

6. CONCLUSIONS

In this work we have implemented propagation models for the underwater acoustic channel within the framework of the USARSim robotics simulator by extending the WSS plugin. Our models are based upon accepted theoretical models and provide results which are as close to off-shore performance as possible. Furthermore, using a simulator with a realistic physics engine ensures further accuracy. The calculate a multipath interference likelihood based upon sub-bottom profile is unique to our implementation and provides a feature that could help researchers build systems which minimize effects of this phenomenon.

REFERENCES


