Homing an Unmanned Underwater Vehicle Equipped with a DUSBL to an Unmanned Surface Platform: A Feasibility Study

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***Abstract*—The overall objective of this work is to evaluate the ability of homing and docking an unmanned underwater vehicle (Hydroid REMUS 100 UUV) to a moving unmanned surface vehicle (Wave-Adaptive Modular Surface Vehicle USV) using a Hydroid Digital Ultra-Short Baseline (DUSBL) acoustic positioning system (APS), as a primary navigation source. An understanding of how the UUV can rendezvous with a stationary platform first is presented in this paper. Inherently, the DUSBL-APS is susceptible to error due to the physical phenomena of the underwater acoustic channel (e.g. ambient noise, attenuation and ray refraction). The development of an APS homing simulator model has allowed the authors to forecast the UUV's position and the estimated track line of the USV as determined by the DUSBL acoustic sensor. The model also provides the associated cross-track (horizontal), down-range (vertical), and along-range (projected) body-fixed errors to be expected in discrete periods of time for any sound velocity profile. In this model, focus is placed on three main elements: 1) the acoustic channel and sound ray refraction when propagating in an in-homogeneous medium; 2) the detection component of an ideal DUSBL-APS using the Neyman-Pearson criterion; 3) the signal-to-noise ratio (SNR) and receiver directivity impact on position estimation. The simulation tool is compared against actual open water homing results in terms of the estimated source position between the simulated and the actual USBL range and bearing information.**

Keywords— USBL; homing; docking; underwater navigation; unmanned underwater vehicle; unmanned surface vehicle; underwater acoustics positioning

I. INTRODUCTION

The goal of this joint project is to develop and demonstrate a modular design that allows an unmanned surface vehicle (USV) to operate in a swarm configuration with several other USVs, and have the payload capacity and capability to carry, launch, home, dock, recharge, and download data with an unmanned underwater vehicle (UUV). Docking a UUV onto a moving USV can be a daunting task due to maintaining vehicle stability in current and wave action, as well as maintaining signal integrity for acoustic communication. The implementation of heterogeneous, autonomous marine vehicles that can cooperatively work together to perform a mission is still a fairly novel field of research. For example, in [7], a research group from Kongsberg Hydroid was able to dock the REMUS 100 UUV, equipped with proprietary software, to a system that was towed behind a surface vessel using a USBL acoustic positioning system. The outcome of the mission showed that mobile docking is certainly possible. However, the ability to fully capture and recover the UUV from the surface, as well as provide charge and transfer data while still moving requires further time in development.

This project is part of a collaborative research performed by several universities as a part of the Atlantic Center for the Innovative Design & Control of Small Ships (ACCeSS) program [3]. The program consists of faculty, scientists, and graduate students from various universities (Stevens Institute, Webb Institute, University College London, United States Naval Academy, United States Naval Postgraduate School, George Mason University, Florida Atlantic University), with specializations ranging from hydrodynamics to system and sensor modeling, simulation, and implementation. The research promotes advancement of integrated hull design, and shipboard automated systems to perform cutting edge tasks for military and industrial applications.

Experimental testing is implemented using two unique vehicles. The Wave Adaptive Modular Vehicle (WAM-V, shown in Figure 1), is an unmanned, catamaran style surface vessel with shock dampers designed for stability enhancement when carrying payloads (such as a UUV). The underwater vehicle used is the Kongsberg Hydroid REMUS 100 UUV equipped with a Hydroid Digital Ultra-Short Baseline (DUSBL) APS (also shown in Figure 1). The WAM-V is equipped with a homing transponder that the REMUS 100's DUSBL system acoustically interrogates to acquire the position state between the two vehicles [4]. The WAM-V is also modified with an autonomous Launch and Recovery (LAR) system that will have the capacity to carry the REMUS 100 [8].

Sponsors: Atlantic Center for Innovative Design and Small Ships Program; Office of Naval Research (Kelly Cooper, code 33) under ONR contract number N000141110926.

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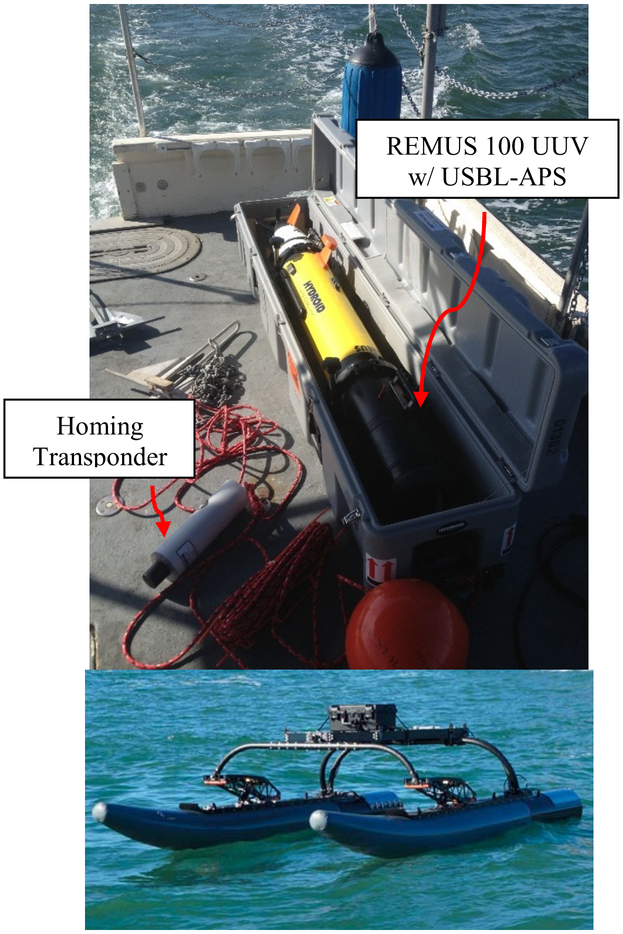

Figure 1: Hydroid REMUS 100 UUV equipped with a DUSBL-APS and the homing transponder (top) and Wave Adaptive Modular Vehicle (WAM-V, bottom); courtesy of Marine Advanced Research Inc.

The major challenge of this project that separates it from previously documented UUV homing and docking projects is the unmanned launch and recovery of the UUV while the USV is still moving in an independent track. There are physical characteristics of the acoustic channel that dramatically affects the elevation, range, and bearing values that are acquired. The challenge is that these physical characteristics are both space and time variant, causing possible change from one location to another. The robustness of the system to the acoustic channel directly affects the ability of the vehicle to successfully dock with the surface platform.

To determine the feasibility of homing the REMUS 100 UUV to the WAM-V platform, the UUV is first required to home to a fixed source. This allows the ability to analyze the system and gain practical understanding of the REMUS 100's behavior when using the DUSBL-APS for navigation. The content of this paper provides basic understanding, allowing growth to the next phase of the project (homing to a moving source) which will be presented in subsequent publications.

II. DUSBL-APS DYNAMIC MODELING

A. Overview

For this project, the Hydroid DUSBL-APS is the primary navigation sensor for the UUV to home to the acoustic source. The APS provides three body-fixed components of information: slant range, azimuthal bearing, and the elevation bearing to the desired source [4]. From a dynamic modeling standpoint, focus is placed on accurately determining the received azimuthal and elevation bearings. The slant range calculation is a straight forward process; it is directly a function of the average acoustic time of travel from the source to the DUSBL receiver, the estimated sound speed in the local fluid, and accuracy of the system [4]. The azimuthal and elevation bearings are more complex to model due to multivariate uncertainties.

The ability to home a UUV to an unmanned platform requires the UUV to track the unmanned source and adapt its behavior to the changing environment to minimize error in positioning fixes, thus increasing overall homing reliability. Our dynamic estimation incorporates effects of the acoustic channel and the computing uncertainty generated by the navigation system itself. The expected errors are in the estimated target slant range $\hat{r}_s$, target azimuthal bearing $\hat{\theta}$, and the target elevation bearing $\hat{\varphi}$ of the source. The various sources of error depend on the signal to noise ratio (SNR), direction of acoustic arrival at the receiver, and acoustic time of travel estimate; the three most important parameters needed for underwater acoustic positioning.

The induced error is caused by five major components that are currently known to affect the quality of underwater acoustic positioning: 1) system update rate; 2) intermittent communication 3) subsurface obstacles; 4) water current; 5) physical properties of the acoustic channel.

The homing simulation algorithm (Figure 2) models the acoustic propagation, and the received signal, based on ambient noise and transmission losses. The simulator calculates the associated errors (vertical, horizontal, and projected) expected for each navigation update.

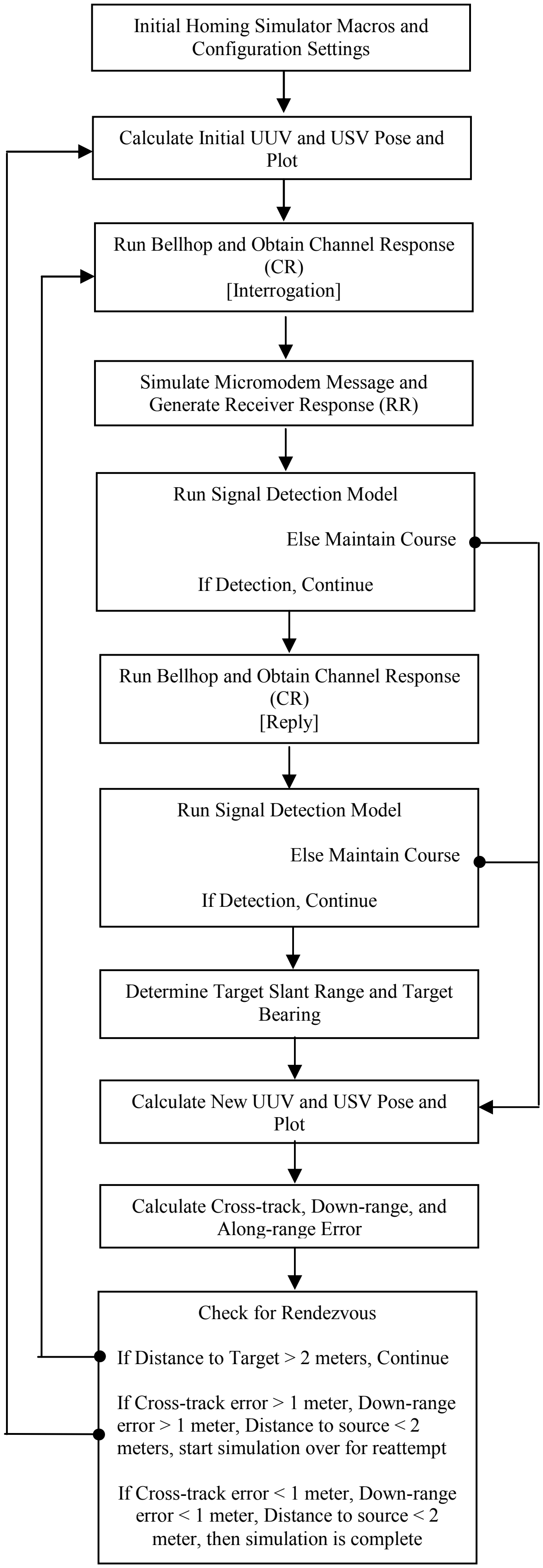

Figure 2: The simulator algorithm.

B. Modeling The Underwater Acoustic Channel

To emulate sound propagation, the source interrogation and transponder reply messages are modeled using a finite element ray (FER) tracing algorithm; Bellhop, as provided by the Ocean Acoustic Toolbox [4,7]. Using open-source software allowed in-house development to be focused on analyzing the signal detection component of the APS, and deriving a set of dynamic equations that can forecast the estimated errors in range and bearing to the transponder.

The FER trace output provides the channel response (CR) given a prescribed sound velocity profile (SVP). In particular, it provides information such as normalized receive amplitude, phase, time of travel, number of surface bounces, and number of bottom bounces. Channel details are also accounted for by providing surface wave profile, seabed profile, half-space attenuation properties, and transducer directivity. The FER trace is used to determine the eigenray time series and provide arrival information based on the receiver's response given the presence of ray refraction and ray multipath.

Here, the authors simulate operations in shallow water along the coast of South Florida. In 2003, a series of measurements were conducted at the South Florida Ocean Measurement Center (located just south of the homing test site) to monitor the environment along the coast. The data collected included conductivity and temperature using MicroCAT conductivity and temperature sensors placed at various depths. The data was merged to develop the local sound velocity profile as seen in Figure 3. Although these data are not recent, they were collected near the test field used in this research at a similar time of the year. The image on the left shows the measured data with a corresponding sound velocity profile and the image on the right shows the profile that was generated and used in the homing simulator.

Figure 4 shows a simulated eigenray trace. In particular, it shows the sound propagation (including multipath) of a reply from the homing transponder, located at 3 meters depth, to the USBL receiver, located at 10 meters depth. The spacing between is 200 meters. These positions represent the homing start point for a defined mission. The green line is line drawn from source to receiver and represents a perfectly straight ray path that can be used as a reference line (this line is not part of the actual simulation). The two red lines show the most direct simulated arrivals (the eigenrays) to the receiver. It can be seen that the red lines have shown some curvature associated with upward refraction, caused by the sound velocity gradient in the water column. In turn, their directions of arrival are different from the straight path (in green), revealing that there must be a bias in the direction of arrival estimate. The blue lines (rays with minimal surface and bottom bounce) and black lines (rays with lots of surface and bottom bounce) represent multipath rays that are filtered from the modeled time series when using the arrival information.

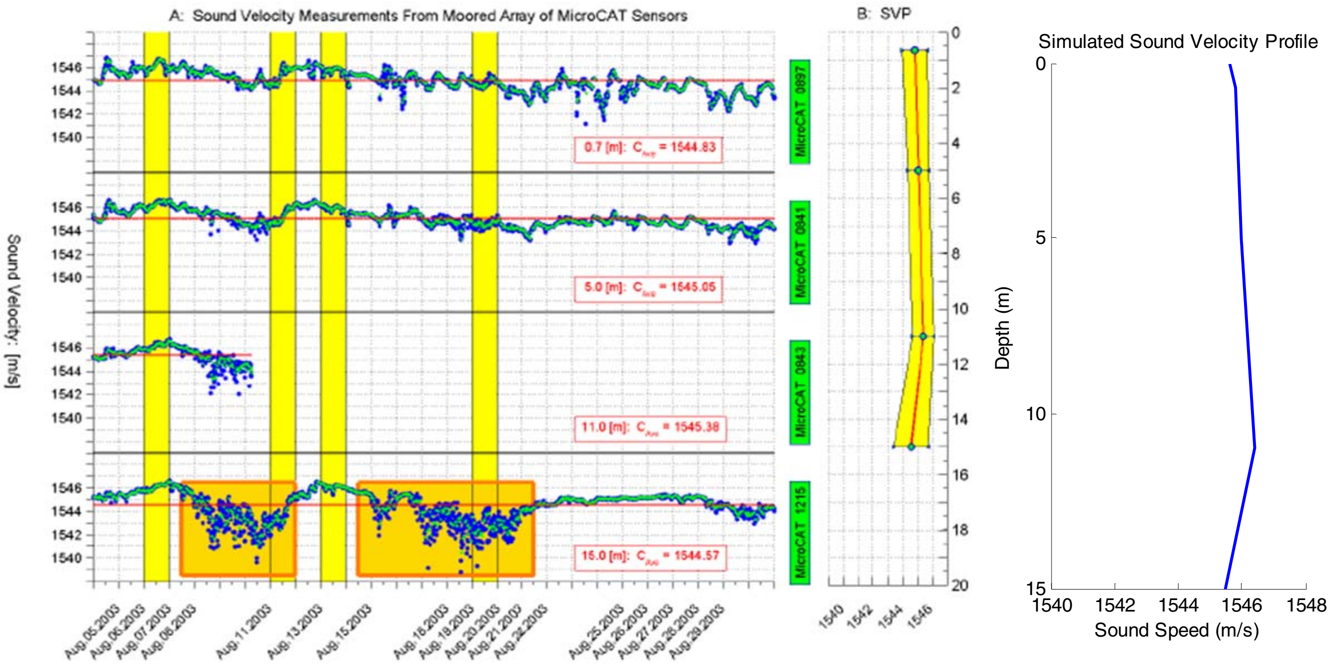

Figure 3: Left: Sound velocity measurements collected during the 2003 coastal observation. The data was collected using MicroCAT conductivity and temperature sensors located as various depths. Right: Actual sound velocity profile used in simulation.

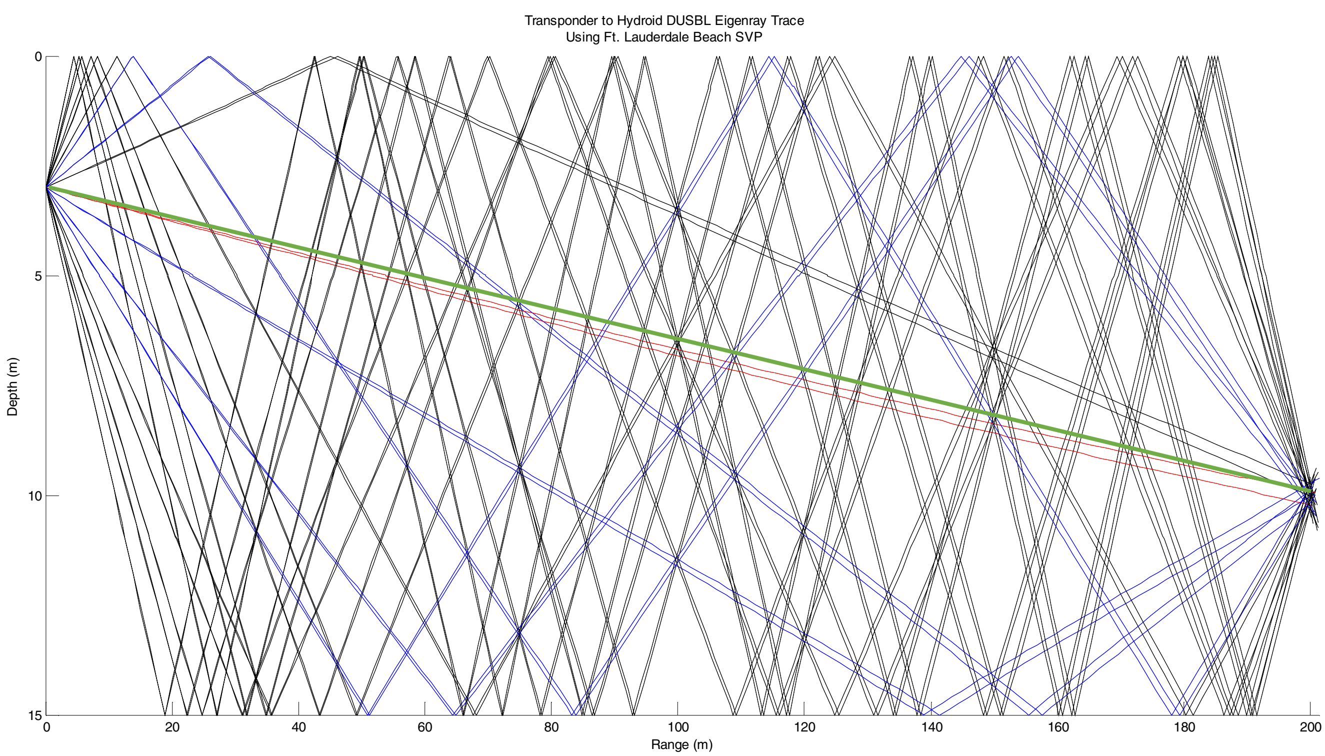

Figure 4: Eigen trace produced during the simulation. The ray transmission of a reply from the homing transponder located at 3 meters depth, to the DUSBL receiver located at 10 meter depth. The red lines show the direct arrival rays. The green line represents a straight line ray path in which can be used as a reference line to compare ray curvature.

C. DUSBL-APS Sonar Model

The DUSBL receiver combines a four channel hydrophone array and a digital signal processor to a four-channel acquisition system. Each channel is equipped with a variable gain pre-amplifier (VGA) and a band-pass filter. The processor performs matched filtering, signal detection, and estimates the range and bearing to the acoustic source [1,2]. The broadband signal used by the DUSBL-APS accommodates limited amounts of Doppler shift [5]; The DUSBL-APS system is simulated and operated within the limits recommended by the manufacturer [4].

The acceptable directivity (shown in Figure 5) requires that the ray path exists within ±17.5º of bore sight of the receiver, thus providing a 35º cone of acceptance [4]. The transmitted signal bandwidth is expected to be within 25-30 kHz (26 kHz interrogation and 29 kHz reply – as measured in lab), which also accommodates a Doppler spread of approximately 96.7 Hz when operating at differential speed of 5 knots relative to its target.

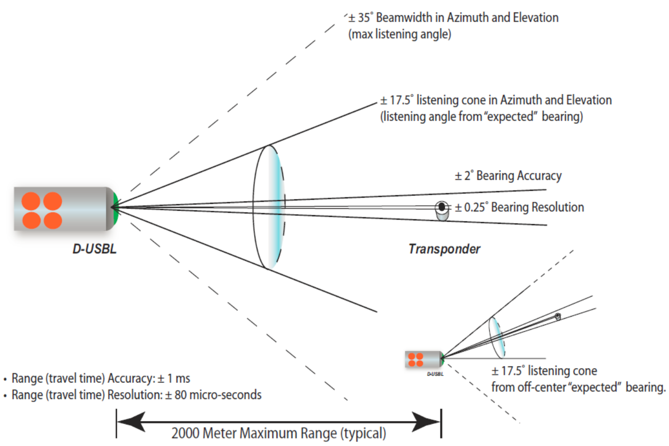

Figure 5: The directivity of the DUSBL receiver and its associated accuracies. The cone of acceptance is ±17.5º from bore sight of the receiver's sensitivity pattern. The image is a courtesy of Hydroid.

The signal quality is directly affected by the acoustic refractions since the added traveling distance of the ray allows for more attenuation, which thus lowers the signal-to-noise ratio (SNR). The directivity of the receiver antenna, the ambient noise (conveniently modeled as additive white Gaussian noise), and the reverberation of the source signal from the sea surface and sea bottom are the main factors affecting the SNR [9].

SNR degradation is in great part due to the additive background noise, which will produce frequent, intermittent interruptions in signal detection. Noise produced due to pressure perturbation in the presence of heaving waves can be neglected since most of this spectral power occurs at a frequency below the operating bandwidth of the DUSBL-APS. Biological sea life such as snapping shrimp, and the boat traffic in the area also add to the ambient noise. According to reference [9], the average noise power spectral density (PSD) at 25 kHz is approximately 40 dB re 1 µPa/√Hz in the Ft. Lauderdale area when wind speed is approximately 7-10 knots. Intermittent noise can be found up to 5-10 dB higher.

To estimate the SNR value, the source power spectral density, G_s, and the squared value of the channel's amplitude response, $H(f)$, are used to generate the received power spectral response, G_R,

$$G_R(f) = |H(f)|^2 G_s(f) \tag{1}$$

Using the generated source spectral response, the total received power of the desired signal, π_{rec}, is estimated as,

$$\pi_{rec} = \sum_{k=1}^{K} G_R(k\Delta f)\Delta f \tag{2}$$

where, Δf is the differential frequency of the power spectrum, and k is an index counter with upper K being the maximum number of indices in the PSD. The SNR value can then be approximated as a function of the power received and the average noise PSD N_0 across the operating bandwidth B,

$$SNR(\pi_{rec}, N_0, B) = 10 \log\left(\frac{\pi_{rec} + N_0 B}{N_0 B}\right) \tag{3}$$

Using the Neyman-Pearson detection criterion [2], the probability of detection is generated by comparing the SNR value to a desired detection threshold coefficient, *DT*. A detection is made if,

$$SNR(\pi_{rec}, N_0, B) > DT \tag{4}$$

D. DUSBL-APS Navigation Model

The DUSBL-APS navigation performance is measured using the numerical solutions provided by simulation, and using data collected from open water testing. When using the APS as the primary navigation source, the overall homing performance is directly coupled to the SONAR performance due to the system update rate. In such case, the navigation performance inherently becomes variant on the signal quality and acoustic ray direction of arrival (DOA).

The USBL-APS update rate increases as the UUV approaches the homing transponder due to shorter travel-time and increased signal spectral power, which leads to increased detection probability and more valid fixes. The increase in valid fixes improves time and spatial navigation resolution, and reduces unwanted track line overshoot. Due to refraction, the acoustic rays arrive at the transducer at uncertain angles, causing the signal-to-noise ratio to fluctuate with respect to the receiver's directional sensitivity. The bias in the true bearing to the source is proportional to the amount of sound wave refraction in the water. This occurs in 3D space, consisting of a vertical and horizontal plane that contains a body-fixed range and bearing to the acoustic source.

Figure 6 is an illustration of the homing process in reference to the vertical plane (XZ plane). Every 30 seconds, the UUV will interrogate the homing transponder in attempt to acquire a valid fix. A fix is considered valid if the ray arrives within the cone of sensitivity of the receiver and the SNR value received is greater than the detection threshold of desired bandwidth. The concentrated view shows a refracted ray entering within the sensitivity of the receiver at a nominal angle, φ'. The actual true bearing to the source is defined as φ_s. The difference between the two is the nominal navigation bias. As a result, the source location measured by the DUSBL-APS falls within a cone of error.

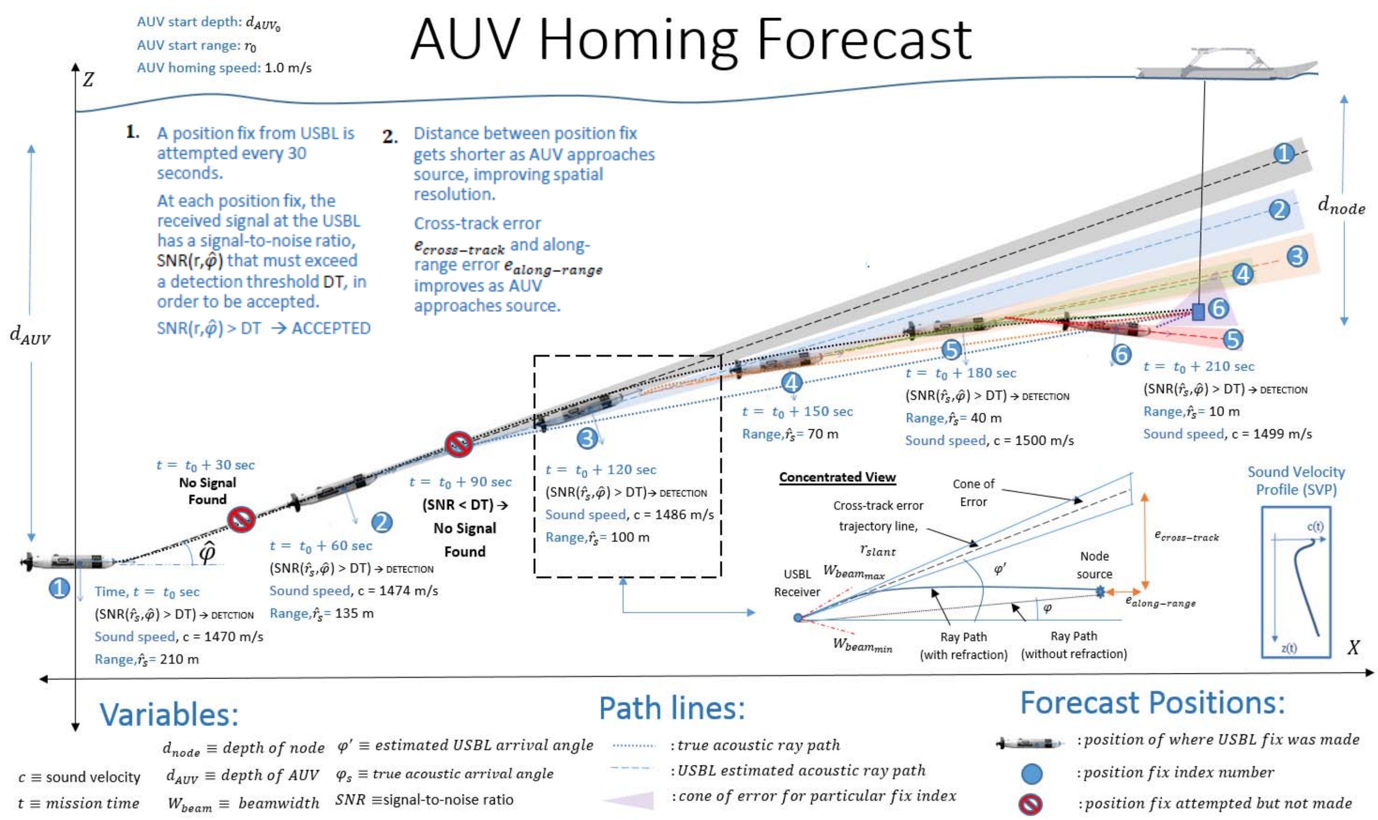

Figure 6: Homing process: A position fix is attempted every 30 seconds. If a signal is received, it is passed through a signal detector to determine if it is the desired signal. A signal is determined valid if the SNR value is larger than the detection threshold, DT within a specified frequency band. The concentrated view shows the acoustic ray path relative to the vertical plane. The nominal value received, φ', is the actual direction of arrival with acoustic refraction. The uncertainty due to signal processing and ray path curvature creates a cone of error, along with a cross-track and along-range error.

In the vertical plane, the ray refraction affects the elevation bearing. In the horizontal plane, the ray refraction affects the azimuthal bearing. In the result section, we assume that horizontal ray refraction is negligible. The simulated bearing is simply estimated as the true bearing to the source, plus bias due to the ray refraction, plus bearing uncertainty due to processing noise in which generates a cone of error. According to manufacturer specifications the processing noise is +/- 2 degrees [4].

The range calculation is also affected by both planes. In best case scenario the acoustic ray has no refraction and so it travels in a straight line, which would also be the most direct ray and thus produce the most accurate position estimate. In the case of a refracted ray, the frontal wave has to travel further due to the added arc length in the vertical and horizontal directions of the ray path [5]. The range calculation is simply a function of the local sound speed and of the two-way time between source and receiver, $\hat{T}_1$and $\hat{T}_2$ respectively, as it varies with the traveled ray distance, r'.

The homing transponder also has a processing turnaround time which occurs to respond to the receiver. This time is approximately 800 ms according to manufacturer specifications [4]. This time, however, is deducted by the DUSBL-APS after it has calculated the two-way time of travel, and so can be neglected in the range model. However, there is an amount of time, Δt, that needs to be factored in due to uncertainty in processing time it takes to detect the signal. The jitter, according to manufacturer specifications, ranges within +/- 1 ms of the average time it take to detect the signal [4].

Equation (5) shows a mathematical formulation of the described estimated elevation bearing, azimuthal bearing, and slant range to the source,

$$\begin{bmatrix}\hat{\varphi}\\ \hat{\theta}\\ \hat{r}_s\end{bmatrix} = \begin{bmatrix}\varphi_s(\varphi',r,C(z)) & \delta\varphi(r,c(z)) & \Delta\varphi(\varphi',SNR(r,\theta',\varphi'))\\ \theta_s(\varphi',r,C(z)) & \delta\theta(r,c(z)) & \Delta\theta(\theta',SNR(r,\theta',\varphi'))\\ \hat{T}_1(r')+\Delta t_1 & \hat{T}_2(r')+\Delta t_2 & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{1}\\ \mathbf{1}\\ \boldsymbol{C/2}\end{bmatrix} \quad (5)$$

where φ_s is the true elevation bearing to the source, $\delta\varphi$ is the elevation bias due to ray refraction and $\Delta\varphi$ is the uncertainty in elevation bearing due to processing noise. In the horizontal plane, θ_s is the true azimuthal bearing to the source, $\delta\theta$ is the azimuthal bias due to horizontal ray refraction and $\Delta\theta$ is the uncertainty in azimuthal bearing due to system accuracy.

As illustrated in Figure 6, the definition of each term applied to generate Equation (6),

$$\begin{bmatrix}\hat{\varphi}\\ \hat{\theta}\\ \hat{r}_s\end{bmatrix} = \begin{bmatrix}\varphi_s & \left(\varphi' - \tan^{-1}\frac{|Z_{USBL}-Z_S|}{|X_S-X_{AUV}|}\right) & \Delta\varphi\\ \theta_s & \left(\theta' - \tan^{-1}\frac{|Y_S-Y_{AUV}|}{|X_S-X_{AUV}|}\right) & \Delta\theta\\ \hat{T}_1(r')+\Delta t_1 & \hat{T}_2(r')+\Delta t_2 & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{1}\\ \mathbf{1}\\ \boldsymbol{C/2}\end{bmatrix} \quad (6)$$

where C=1500 m/s is the pre-programmed average local sound speed referenced by the DUSBL, Z_{USBL} is the depth of the USBL receiver and Z_S is the depth of the source where z is positive downward. Using a North, East, Down (NED) frame, X_{USBL} is the north position relative to the USBL's homing start point and X_S is the source's north position relative to the USBL's homing start point. Also, Y_{USBL} is the east position relative to the USBL's homing start point and Y_S is the source's east position relative to the USBL's homing start point. The start point is defined as the waypoint at which the UUV commences the homing control loop in the mission plan.

III. SIMULATION AND EXPERIMENTAL HOMING RESULTS

The analysis and performance estimation of the DUSBL-APS can be broken down into two major components: SONAR performance and navigation performance. Each component is provided with a simulation model and experimental analysis conducted in the field. To validate the simulation results, open water homing tests were conducted in coastal waters (approximately 1 mile offshore) off Fort Lauderdale, Florida. The major challenge of this test is accurately determining the UUV position relative to the acoustic source at the point of the docking attempt (rendezvous point). To do so, a 1.2 meter by 1.2 meter target was deployed on the seafloor bottom, in which moored a surface buoy. Figure 7 illustrates the experimental setup.

The mission plan consists of a 200 meter transit (186.7 meters in open-water experiment due to some deployment positioning error) with a homing start depth of 10 meters. The homing leg requires the vehicle to ascend to 5 meters depth, the same depth in which the transponder is moored. Located just above and below the transponder is a docking tube, designed to allow the vehicle to dock using the project's first generation latching mechanism. The drop target on the seafloor is used as a marker to visually identify (from "birds-eye view" with an underwater camera) how far away the UUV is from the homing transponder as it approaches. The field homing test was successful; the vehicle was able to latch to the docking tube located on the mooring line of the drop target.

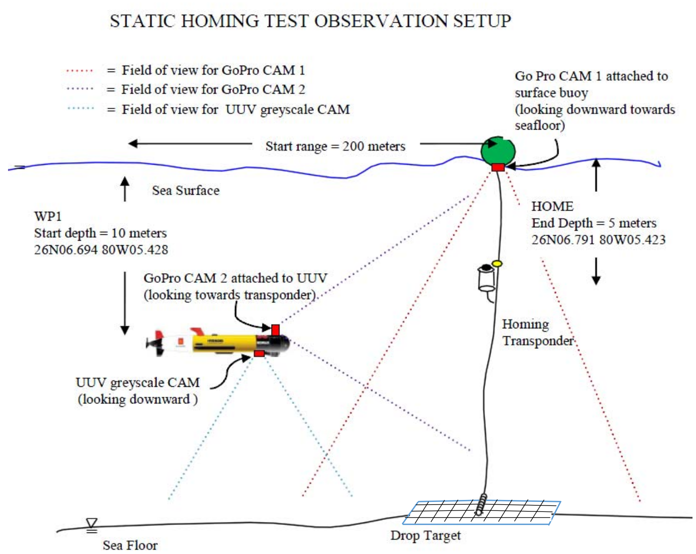

Figure 7: Experimental setup for homing test.

The main interest of this research is to determine the overall estimated accuracy of homing the UUV to the acoustic source. Such errors are labeled as the estimated cross-track error $\hat{e}_{CT}$ and estimated along-range error $\hat{e}_{AR}$. It is of most interest to view the impact on the vertical bearing since it is most susceptible to acoustic ray refraction, and thus generates most of the cross-track bias.

The simulation shows that the vehicle should have received about six fixes during the 200 meter transit. In all, the overall vertical cross-track error would be 0.221 meters and the overall horizontal cross-track error would be 0.534 meters as seen in Figures 8 and 9. Figure 10 clearly shows that the vertical cross-track error converges towards zero as earlier predicted. Figure 11 in particular reveals that much of the error is due to the system uncertainty as it begins to develop a random walk, shown in red. The ideal system, shown in green, would contain no time jitter (although still biased due to ray refraction), and thus provides much smoother and reliable positioning estimates. In either case, the overall cross-track errors (both vertical and horizontal) are less than 1 meter, which shows that the simulation expects the UUV to accurately home to a fixed platform.

Looking at the experimental results in Figure 12, the UUV reached a maximum depth at the starting point of 11.31 meters, which is just deeper than the starting point in the simulation, and may account for the slightly steeper ascent angle (nearly 5 degrees, as compared to nearly 3 degrees respectively). Also the first fix may have required the UUV to ascend at its starting pitch until it approaches the same known depth as the homing transponder. This would allow the UUV to follow a line of sight track much easier since ray refraction would be limited assuming that sound speed is conserved when operating at constant depth.

The experimental homing result shows that the vehicle successfully acquired 10 position fixes utilizing the DUSBL APS, in which 90% of the fixes were within 75 meters the fixed platform.

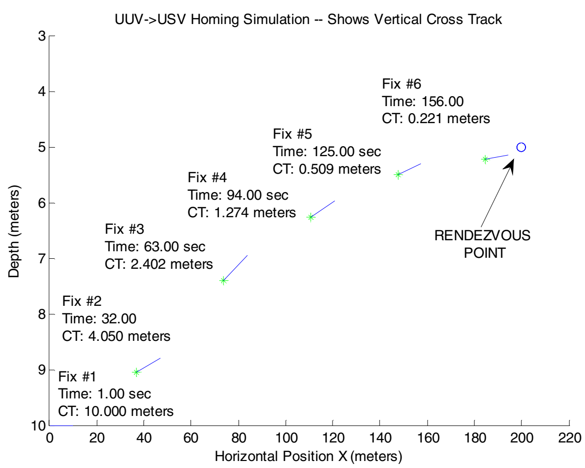

Figure 8: Vertical cross-track results produced by the homing simulator. In particular, it shows the homing process in the vertical plane, along with the cross-track (CT) errors at each fix index.

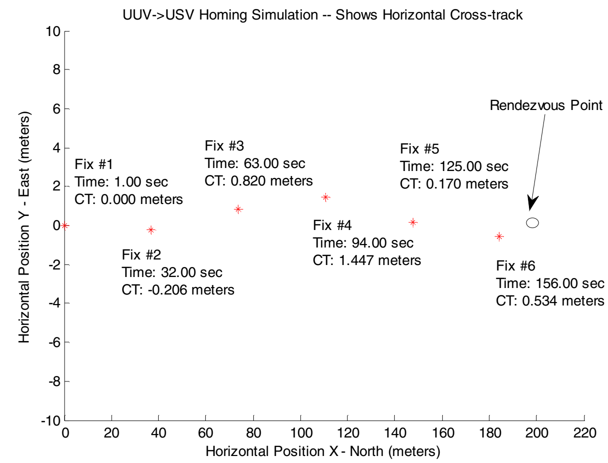

Figure 9: Horizontal cross-track homing simulator output. This view shows the horizontal navigation plan, which corresponds to the estimated azimuthal bearings. It also shows the associated horizontal cross-track (CT) error.

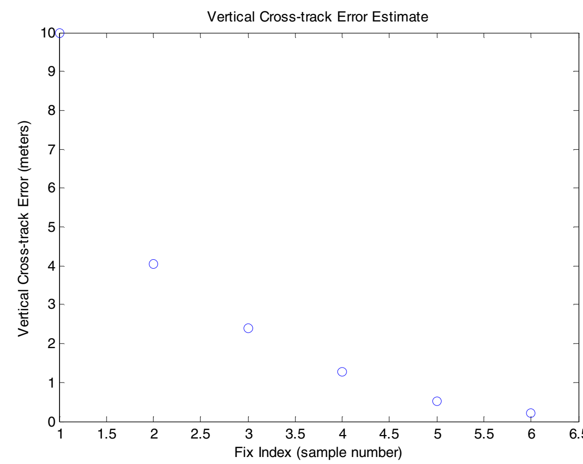

Figure 10: Cross-track error converges towards zero as the fix index increases (thus the vehicle is getting closer).

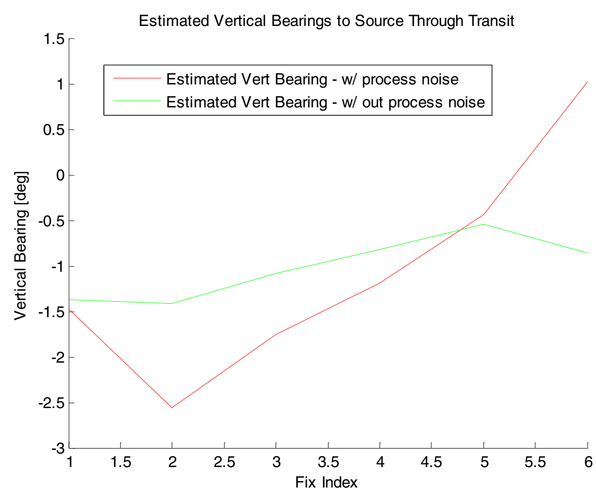

Figure 11: Calculated vertical bearing estimate from each acquired fix with and without process noise.

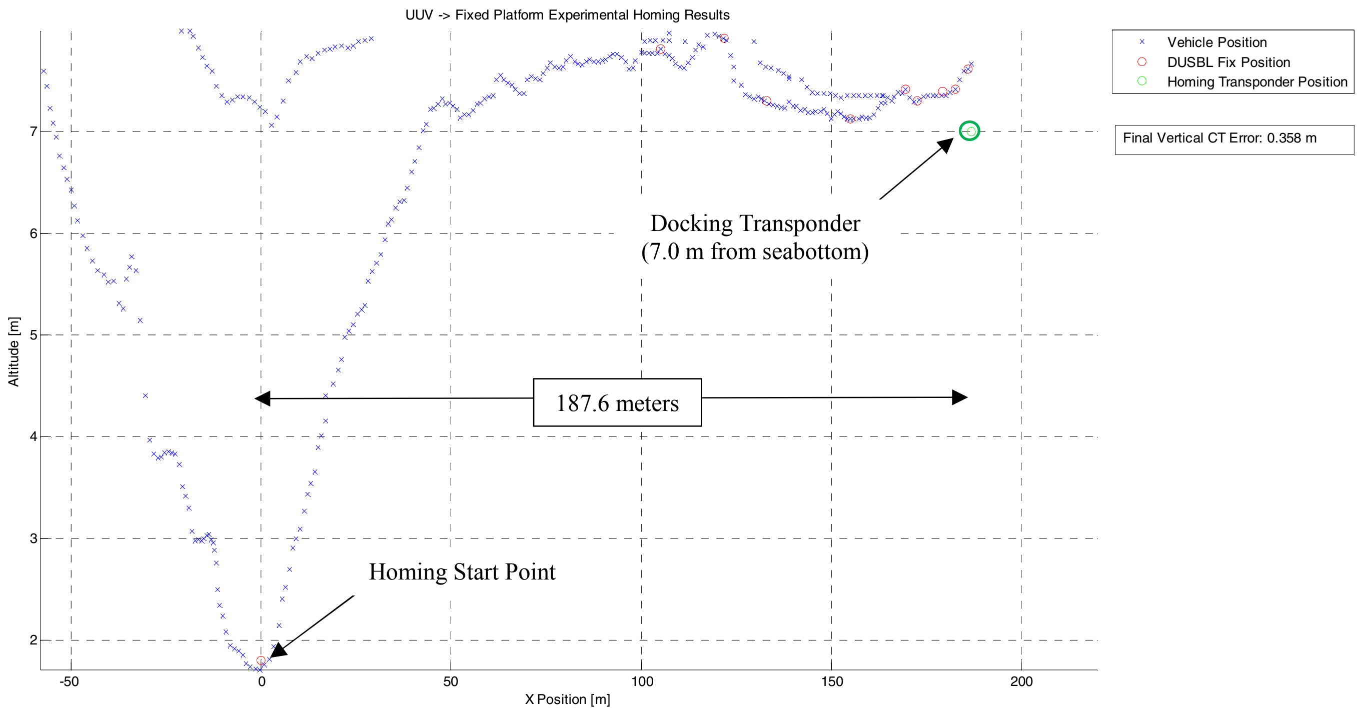

Figure 12: Experimental homing results in open water testing. The UUV was successfully able to dock within 0.358 meters of the homing transponder using 10 acquired fixes (represented as red circles). Horizontal homing distance was 186.7 meters (after deployment).

Figure 13 shows the SNR values recorded by the UUV. Although the values are somewhat noisy, there is clearly an upward trend as the vehicle approaches the homing transponder. This indicates that the SNR value improves, and thus so does the ability to detect the signal as the UUV gets closer. Figure 14 shows an image taken from the Hydroid VIP program of the horizontal track line recorded by the UUV [4].

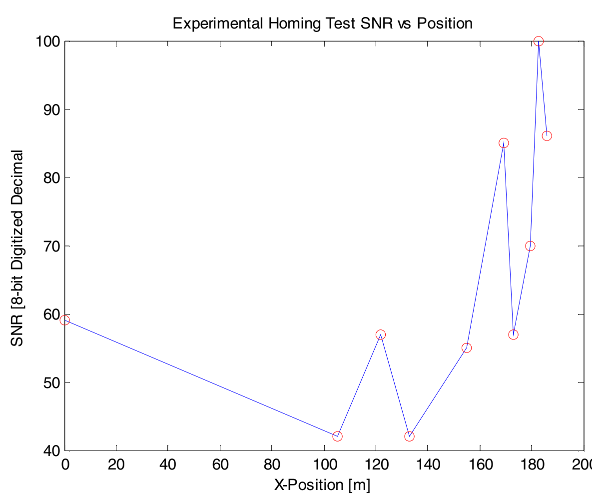

Figure 13: SNR values data logged by the REMUS 100.

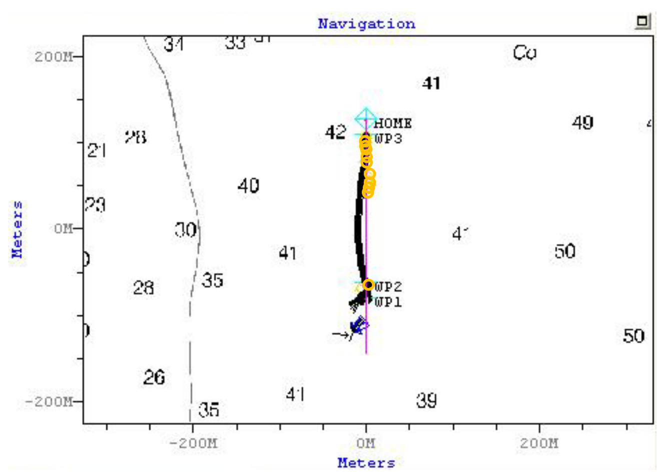

Figure 14: UUV track during homing transit. Yellow circles represent a valid USBL fix.

Conclusion

Overall, the UUV's data shows that it was capable of latching to the docking tube moored to the drop target with a final vertical cross-track error of 0.358 meters. In such case, the simulation and experimental data show the vehicle to have the capability to dock within 1 meter of accuracy. Such results give promising outlook to having the ability to home and dock an unmanned underwater vehicle with a moving surface platform as the next phase of this project.

ACKNOWLEDGMENT

The authors wish to thank the Technical support office at Kongsberg Hydroid, as well as Tom Austin (WHOI), with help on the REMUS 100 and DUSBL-APS. Also a special thanks to Michael Porter for help with the Bellhop interface. This work is sponsored by the Office of Naval Research (Kelly Cooper, code 33) under ONR contract number N000141110926.

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