Experimental Evaluation of a USBL Underwater Positioning System

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***Abstract*—This paper presents and experimentally validates two closed-form underwater acoustic positioning methods with experimental data from an Ultra-Short Base Line (USBL) system developed from scratch. The prototype underwater positioning device that is being developed is planned to be extensively used within the framework of the European TRIDENT project. Both positioning methods compute the localization of a transponder relatively to the USBL using the time of flight of underwater acoustic waves. Based on spread-spectrum signal processing techniques, specially designed Direct Spread Spectrum Signals (DSSS) are employed to improve the performance of the system and tackle multi-path detection problems and detectability in the presence of noise. A validation of the positioning schemes was conducted with experimental data using the USBL inside a harbor yielding satisfactory preliminary results and good performance.**

I. Introduction

Recent advances in key technological aspects related with marine research enabled the scientific community to direct its efforts towards upgrading underwater robotic vehicles with higher autonomy in marine intervention tasks to be carried out at sea. Several goals such as autonomous perception, task recognition, and intervention with robotic manipulators are subject to ongoing research (see [1], [2] and references therein). Intervention Autonomous Underwater Vehicles (I-AUVs) find application in a wide variety of research and commercial threads ranging from marine salvaging, environmental monitoring and surveillance, underwater inspection of estuaries, harbors, oil-rigs, and pipelines, and geological and biological surveys.

Out of several systems like robotic arm manipulators, thrusters, rudders and fins, one key role is played by the navigation system on board marine surface and underwater robotic vehicles, that allows for the vehicles to navigate relative to either a fixed coordinate frame or relative to another vehicle for cooperative navigation and homing/docking operations. Moreover, the development of these navigation systems has to bear in mind key features such as low-cost, compactness, high performance, versatility and robustness.

From the myriad of available underwater navigation aiding sensors such as Doppler Velocity Loggers (DVL), depth pressure sensors, and magnetic compasses, acoustic positioning systems (see [3], and [4]) like Long Base Line (LBL), Short Base Line (SBL), and Ultra-Short Base Line (USBL) stand often as the primary choice for underwater positioning (see [5], [6], and [7]). The USBL sensor consists of a small and compact array of acoustic transducers that allows for the computation of a transponder position in the vehicle coordinate frame, based on the travel time of acoustic signals emitted by the transponder. The measurements provided by these systems have very low update rates (typically below 1 Hz) imposed by physical limitations and mission specific constraints (velocity of acoustic waves in the water, multi-path phenomena, and other disturbances), with a performance that degrades as the transponder/USBL distance increases.

This paper presents two closed-form methods of estimating the transponders positions in the USBL reference frame, and aims to experimentally validate this positioning schemes with real world experimental data from a USBL developed from scratch [8]. The first method resorts to the planar approximation of the acoustic waves arriving at the USBL array which is suitable for long-range operations (such as a vehicle homing to a station) as the distance between the USBL and the transponder is much larger than the baseline of the array. The second method that is presented does not employ the planar-wave approximation and maintains the underlying nonlinear framework. The consideration of this latter method follows from the needs of accurate positioning at very close-range operations (such as docking operations of an underwater vehicle to an Autonomous Surface Craft that will be considered in the TRIDENT project), where the planar-wave approximation might not be valid.

The paper is organized as follows: first Section II presents the closed-form USBL positioning methods preceded by some background details on the acoustic signaling and processing. Section III presents some hardware implementation details, description of the conducted sea trials, and the experimental results of the positioning schemes. Finally Section IV provides some concluding remarks and comments on future work.

II. USBL Positioning methods

For any coherent detection problem, a good estimate of the Time-Of-Arrival (TOA) of a signal may be obtained by passing the input signal through a matched-filter whose impulse response is a time-reversed replica of the expected signal [9]. In ideal conditions, the filter output is related to the autocorrelation function of the received signal. Specially designed spread-spectrum modulated signals have known good autocorrelation properties [10] allowing for a sharper output of the matched-filter and improving the performance of the detector. Moreover, good cross-correlation properties can be obtained between several spread-spectrum signals allowing for

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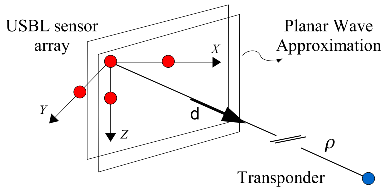

Fig. 1. Planar Wave method

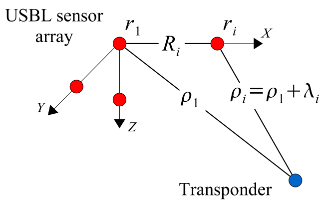

Fig. 2. Spherical Interpolation method

a multi-user configuration in which several entities might be transmitting signals at the same time without interference.

This specially designed signals are typically generated using either Frequency Hopped Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS) codes. In general, spread-spectrum signals have several advantages when compared to conventional signaling (Sinusoidal pulses and CHIRP tone bursts) for underwater range estimation: they present better Signal-to-Noise-Ratio (SNR), robustness to ambient and jamming noise, multi-user capabilities, improved detection jitter, and the ability to better resolve multi-path which is one of the biggest problems in underwater channel acoustic propagation. Closely related work can be found in [11], [12], and in [7].

This section presents two closed-form methods of estimating the transponders positions in a reference coordinate frame. In the first method, the position of the transponders is computed resorting to the planar approximation of the acoustic waves [13], here on referred to as the Planar Wave (PW) method. The latter is based on the equation error formulation presented in [14], referred to as the Spherical Interpolation (SI) method.

A. *Planar Wave positioning method*

For realistic mission scenarios of underwater vehicles the distances between receivers are much smaller than the distances between the sensor array and the transponders, thus the planar wave approximation for the acoustic waves is valid. The PW method is based on that approximation to obtain the range and direction of the transponders. The position is then computed in Body coordinate frame, which origin is considered to be coincident with the centroid of the hydrophones.

Consider the planar wave, the USBL sensor array, and the transponder depicted in Fig. 1. Taking into account the planar wave approximation, the Time-Difference-Of-Arrival (TDOA) between receivers i and k is given by

$$\delta^{(i,k)} = t_i - t_k = -\frac{1}{v_p}\mathbf{d}'\left({}^{B}\bar{\mathbf{p}}_{r_i} - {}^{B}\bar{\mathbf{p}}_{r_k}\right) \tag{1}$$

where v_p is the speed of sound in the water, ${}^{B}\mathbf{p}_{r_g}$ is receiver g ($g \in \{i,k\}$) position on Body frame and $\mathbf{d}$ is the unit direction vector of the transponder ($\|\mathbf{d}\|_2 = 1$).

The vector of TDOA between all possible combinations of N receivers is described, from (1) $\{i = 1,\ldots,N; k = 1,\ldots,N; i \neq k\}$, by

$$\Delta = \begin{bmatrix} \delta^{(1,2)} & \delta^{(1,3)} & \cdots & \delta^{(N-1,N)} \end{bmatrix}'$$

and can be measured directly from signals arriving at the acoustic array. If this capability of measuring the TDOA between all receivers independently is not available, the vector of TDOA can be generated by

$$\Delta = \mathbf{C}\,\mathbf{t}$$

where $\mathbf{C}$ is a combination matrix and $\mathbf{t}$ is the vector of time measurements from all receivers defined as $\mathbf{t} = \begin{bmatrix} t_1 & t_2 & \cdots & t_N \end{bmatrix}'$.

Considering that $\mathbf{t}$ is disturbed by zero mean noise of equal intensity for all receivers, the least squares solution for the transponder direction $\mathbf{d}$ is

$$\mathbf{d} = -v_p \mathbf{S}^{\#}\mathbf{C}\,\mathbf{t}$$

where $\mathbf{S}^{\#}$ is the pseudo-inverse of $\mathbf{S}$ given by

$$\mathbf{S}^{\#} = \left(\mathbf{S}'\mathbf{S}\right)^{-1}\mathbf{S}'\ ,\ \mathbf{S} = \begin{bmatrix} {}^{B}\bar{\mathbf{p}}'_{r_1} - {}^{B}\bar{\mathbf{p}}'_{r_2} \\ {}^{B}\bar{\mathbf{p}}'_{r_1} - {}^{B}\bar{\mathbf{p}}'_{r_3} \\ \vdots \\ {}^{B}\bar{\mathbf{p}}'_{r_{N-1}} - {}^{B}\bar{\mathbf{p}}'_{r_N} \end{bmatrix}$$

Also resorting to the planar wave approximation and taking into account that the origin of the Body frame coincides with the centroid of the acoustic receivers, the range of the transponder to the origin of Body frame can be computed by averaging the range estimates from all receivers. The estimate for receiver h ($h \in \{1,\ldots,N\}$) is computed from $\rho_h = v_p t_h$, and thus averaging for all N receivers yields

$$\rho = \frac{1}{N}\sum_{h=1}^{N} v_p t_h$$

Finally, the relative position of the transponder, expressed in Body frame, is computed by

$${}^{B}\mathbf{p}_{em} = \rho\,\mathbf{d}$$

B. *Spherical Interpolation positioning method*

The Spherical Interpolation (SI) method is based on the equation error formulation presented in [14]. This method computes directly the position of the transponders in Body frame without using the planar approximation. Consider the USBL sensor array and the transponder depicted in Fig. 2.

The relations between the transponder, the reference receiver r_r, and another receiver r_i ($i \neq r$) can be easily established:

$$\rho_r = \|{}^{R}\mathbf{p}_e\|\ ,\ \rho_i = \|{}^{R}\bar{\mathbf{p}}_{r_i} - {}^{R}\mathbf{p}_e\|$$

$$\rho_i = \rho_1 + \lambda_i \tag{2}$$

$$\rho_i^2 = R_i^2 - 2\,{}^{R}\bar{\mathbf{p}}'_{r_i}\,{}^{R}\mathbf{p}_e + \rho_r^2 \tag{3}$$

where ${}^{R}\mathbf{p}_e$ is the position of the transponder in the reference receiver coordinate frame $\{R\}$, ρ_i is the distance between the transponder and receiver r_i, R_i is the distance between reference receiver r_r and receiver r_i, and λ_i is the Range-Difference-Of-Arrival (RDOA) between receiver r_i and the reference receiver r_r.

Replacing (2) in (3) yields

$$R_i^2 - \lambda_i^2 - 2\rho_r\lambda_i - 2\,{}^R\bar{\mathbf{p}}_{r_i}'\;{}^R\mathbf{p}_e = 0 \tag{4}$$

The RDOA measurements must verify the constraint imposed by (4). Due to the noise present in the measurements a constraint violation variable is introduced in (4), according to the so called Equation Error [14]. Thus,

$$R_i^2 - \lambda_i^2 - 2\rho_r\lambda_i - 2\,{}^R\bar{\mathbf{p}}_{r_i}'\;{}^R\mathbf{p}_e = \varepsilon_i \tag{5}$$

where ε_i is the constraint violation variable for the receiver r_i. Considering

$$\begin{aligned}
\delta &= \begin{bmatrix}\cdots & R_{r-1}^2-\lambda_{r-1}^2 & R_{r+1}^2-\lambda_{r+1}^2 & \cdots & R_N^2-\lambda_N^2\end{bmatrix}'\\
\varepsilon &= \begin{bmatrix}\cdots & \varepsilon_{r-1} & \varepsilon_{r+1} & \cdots & \varepsilon_N\end{bmatrix}'\\
\Lambda &= \begin{bmatrix}\cdots & \lambda_{r-1} & \lambda_{r+1} & \cdots & \lambda_N\end{bmatrix}'\\
\mathbf{T} &= \begin{bmatrix}\cdots & {}^R\bar{\mathbf{p}}_{r_{r-1}} & {}^R\bar{\mathbf{p}}_{r_{r+1}} & \cdots & {}^R\bar{\mathbf{p}}_{r_N}\end{bmatrix}'
\end{aligned}$$

the set of $N-1$ equations is given in matrix notation by

$$\varepsilon = \delta - 2\rho_r\Lambda - 2\mathbf{T}\,{}^R\mathbf{p}_e$$

To compute the position of the transponder in the reference receiver coordinate frame, the least squares solution obtained from minimizing the constraint violation energy $J = \varepsilon'\varepsilon$ is given by

$${}^R\mathbf{p}_e = \frac{1}{2}\mathbf{T}^{\#}\left(\delta - 2\rho_r\Lambda\right) \tag{6}$$

where $\mathbf{T}^{\#}$ is the pseudo-inverse of $\mathbf{T}$. Notice that as in the PW method, the set Λ of RDOA measurements can be obtained from $\Lambda = v_p\mathbf{Ct}$ or measured independently if possible.

Thus, the position of transponder in the Body frame can be computed by averaging the estimates (6) for all reference receivers and subtracting the offset from the receivers centroid (origin of the Body frame) to each of the reference receiver.

III. Experimental validation

This section reports the experimental evaluation of the proposed positioning methodologies with experimental data with an USBL array developed from scratch [8]. The preliminary experimental trials were conducted inside a harbor to validate and assess the performance of the system.

A. System description

The tests were conducted inside a harbor in Lisbon, Portugal, where several boats were floating inside the marina besides the floating piers. Combined with a maximum depth of 5 meters, the test conditions were not ideal, in fact rather harsh and quite far from ideal. We feel that the results obtained are even strengthened by this fact. The hardware and signal processing that was used in the harbor trials was presented in [8] and consists of a small array of four hydrophones placed in a non planar 3D configuration with an highly configurable geometry. The receiving acoustic array is depicted in Fig. 3 coupled to its processing workhorse (Digital Signal Processor, acoustic amplifiers, batteries and several other systems). The distance between all hydrophones in the receiving array is approximately 30 centimeters.

The receiving array was tied to a pier and submerged about 2.5 meters underwater. The acoustic transducer that was emitting the DSSS coded signals was placed around 21.5 meters away from the USBL, around 2 meters to the left and 2.5 meters deep, being that both the transmission and reception were synchronized with the GPS 1PPS clock with a precision of $1\mu s$. To generate the DSSS signal, a 127 chips Gold Code was used to BPSK (Binary Phase Shift Keying) modulate a $25KHz$ carrier signal.

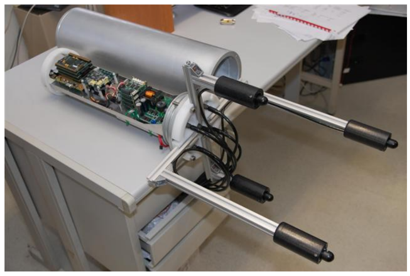

Fig. 3. Prototype system under development: acoustic array and core processing systems

B. Preliminary results

A method of measuring the TDOA between all the receivers was proposed in [8], based on the cross-correlation between the acoustic signals acquired at all the receivers. The preliminary tests presented in [8] using two hydrophones placed horizontally 20 centimeters apart, revealed an improved performance of the cross-correlation method (cross method) when compared to computing the TDOA directly from the TOA computation at each channel (direct method).

The direct method (that computed the TOA on each channel by selecting the matched filter maximum that exceeded a predefined energy threshold), in that particular case revealed a significant deterioration due to multi-path present in the acoustic channel, whereas the cross method was found to mitigate this problem. However, during the implementation and validation of the proposed system using four hydrophones, it became evident that the cross-correlation method also has a severe degradation and incoherence inherited from multi-path present in the channel arriving closely spaced to the direct path. Moreover, using the cross-correlation method might induce errors due to other noise sources that are present in low SNR (Signal to Noise Ratio) scenarios. This fact motivated the further development of the direct method which would bring improved robustness and immunity to multi-path while maintaining an acceptable position repeatability and accuracy.

Thus, a new simpler and more efficient method of measuring the TOA at each channel was introduced in the system and is simply described by: once the signal is detected in the acoustic processing buffers, instead of selecting the peak with the highest correlation (which could perfectly be a secondary path stronger than the direct one), first the output of the matched filter is preprocessed to remove the discrete samples of all the ascending slopes leaving only the local maximums and the descending slopes; finally, a threshold based on the maximum of the output of the matched filter is subtracted from the output of the matched filter and the first occurring non-negative value is selected as the TOA of the signal. In practice a value of 70% of the maximum was found to yield very good results.

The outcome of the positioning strategies with the real experimental data is presented in Fig. 4, after some preprocessing for removal of outliers that violated the physical limitations

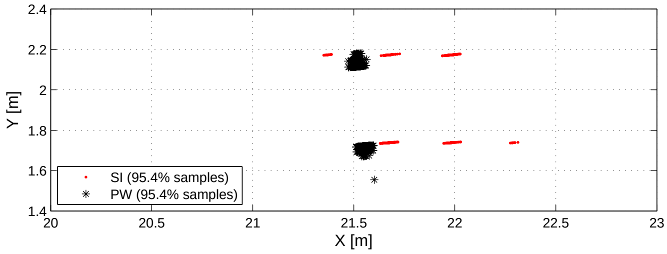

Fig. 4. Positioning methods experimental validation: static position results

of the acoustic array in use. Even thought, the data that was validated and shown in Fig. 4 represent around 95% of the total of 888 performed acquisitions.

From the XY scatter in Fig. 4, it can be seen that the PW method revealed a smaller dispersion of position estimates compared to the SI method for the particular case of this experimental dataset. In fact the SI method revealed more sensitive to the observed TDOA noise than the PW method. As convincingly argued in [15], the SI method should be more precise at closer ranges where the planar-wave approximation of the acoustic wave is not valid. The simulation results presented in [15] predicted a threshold of about 4% the ratio between the baseline and the slant-range of the transponder (baseline of 0.2 cm with a slant-range of 5 m). In this experimental particular case the ratio is about 1.36% (baseline of 0.3 cm with a slant-range of 21.5 m). Thus, experimental trials at closer ranges should in fact be conducted in the near future to validate this assertion with acoustic data.

Two clouds of points are evidenced for the PW method, which are coherent with the overall angle resolution of the array. That is, if only the horizontally spaced hydrophones were used to computed the bearing angle, the angular resolution of the digital implementation of the acoustic system would be around 1.15 degrees. This becomes evident in Fig. 5 that plots the bearing angle that is computed by the PW method and is coherent with the 1 sample acoustic detection noise that was found in the processed dataset.

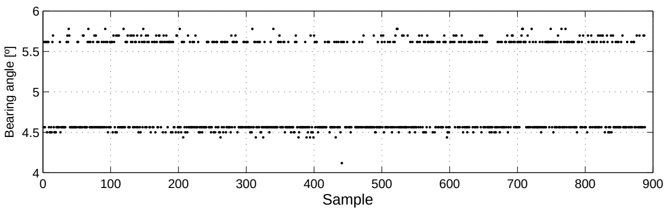

Fig. 5. Bearing angle from PW method

In terms of depth computation for the PW method, the results were quite satisfactory given the test depth, in which around 77.4% of the samples measured a depth of 0 meters (as expected since both the array and the emitter were placed at the same depth) and the remaining measured around 0.43 meters. These results revealed quite satisfactory considering the severe multipath from the bottom and the surface that was expected given the very shallow water channel in which the trials were performed.

IV. Conclusions

This paper presented two closed-form methods of estimating the position of an underwater transponder using an USBL positioning system. A validation of the positioning schemes was conducted with experimental data using a USBL positioning system developed from scratch, yielding satisfactory preliminary results and good performance given the high noise and multi-path test conditions. For the distances considered in the harbor trials, the planar-wave approximation based method revealed to be less sensitive to sensor noise compared to the spherical interpolation method. Future work on this subject will focus on an improved calibration of the acoustic array, test the performance of the system at longer range trials, and the further improvement of the positioning system by experimentally validating USBL fusion techniques with an Inertial Navigation System [16]. On a longer time-horizon it will also focus on taking into account layered underwater sound speed profiles to properly accommodate the varying underwater sound velocity into the filtering framework.

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