2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Design and experimental evaluation of an integrated USBL/INS system for AUVs

M. Morgado, P. Oliveira, and C. Silvestre

Abstract— **This paper addresses the design, development, and test of an integrated Ultra Short Baseline (USBL) and Inertial Navigation System (INS) to be used as a low cost navigation system for underwater robotic vehicles. An architecture for the open prototype is proposed, the acoustic array design and calibration is discussed, the inertial sensors package is presented, supporting acoustic signals to be used are briefly enumerated, and implementation issues are detailed. The system includes also as a by-product the design of a transponder that replies to the interrogations sent out by the integrated USBL/INS system. Preliminary sea tests, conducted in an harbor, are presented to assess the feasibility of the acoustic positioning system, using namely Direct Sequence Spread Spectrum (DSSS) coded signals.**

I. Introduction

The marine habitat naturally poses a huge challenge for systems development mainly due to its harsh environment in which marine robotic vehicles have to withstand high pressures and aggressive metal corrosion. Out of several systems like robotic arm manipulators, thrusters, rudders and fins, one key role is played by the navigation system on board the marine robotic vehicle. The demand for low-cost, compact, high performance, and robust navigation systems that can accurately estimate the underwater vehicle position and attitude, has increased significantly over the past years as this area is being constantly opened to the scientific community and private companies. An interesting overview and survey on the design of underwater robotic vehicles and the inherent technical challenges can be found in [1] and [2].

Previous work by the authors has focused on theoretical studies developing filtering techniques that allowed for the improvement of the performance of the coupling between Inertial Navigation Systems and an Ultra Short Base Line positioning device. In [3], the authors proposed a tightly-coupled fusion technique that showed performance improvements in simulation compared to the commonly used loosely-coupled technique. More recently, an analysis of the achievable performance in simulation of the navigation filters was carried out using the Posterior Cramér Rao Lower Bound [4]. Still, all these techniques lack validation with experimental data, a gap that we plan to bridge over with the prototype system proposed and presented herein.

The proposed integrated navigation system is depicted in Figure 1. The Inertial Measurement Unit (IMU) provides linear acceleration and angular velocity measurements to be processed by the INS algorithm that performs high-speed computations to estimate position, velocity and attitude of the vehicle with respect to a fixed coordinate frame. Using external aiding sensors like the USBL and the magnetometer, an Extended Kalman Filter (EKF) that implements an error model of the INS, estimates position, velocity, and attitude errors that are corrected in a direct-feedback configuration and also compensates for inertial sensors biases. The corrected outputs of the INS can then be used to aid the USBL detection algorithms (Ultra Tightly-Coupled configuration) finding the arrivals of the underwater acoustic signals, as outlined by the fine-dashed connection between the output and the USBL. For further details on the INS algorithms and the information fusion between the USBL and the INS, the reader is referred to previous work by the authors and references therein in [3], [5], [6].

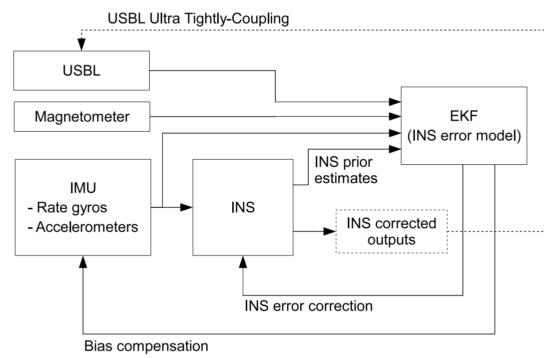

Fig. 1. Integrated navigation system architecture

Several capable and high-performance navigation systems are readily available on the market like the Ixsea Phins underwater INS, the combined USBL+INS+GPS surface tracking system GAPS from IXSEA also, and the long-range USBL tracking device POSIDONIA. LinkQuest also provides lower performance and lower cost USBL systems that can also be submerged. Even though, commercially available solutions do not often allow direct access to the travel times of the acoustic waves on the array receivers. Also, compromised by export regulations that civil companies are subject to, commercial Inertial Navigation Systems have often their outputs downgraded. The combination of these facts and the prohibitive high cost of current commercial solutions conflict with the purpose of designing low-cost marine robotic vehicles.

In this paper, we direct our efforts towards the development of an high performance open navigation research system that bridges the gap between the need to have a system that provides direct access to the Time-Of-Arrival

This work was partially supported by Fundação para a Ciência e a Tecnologia (ISR/IST plurianual funding), by the project PDCT/MAR/55609/2004 - RUMOS of the FCT, and by the EU Project TRIDENT (Contract No. 248497).

The work of M. Morgado was supported by PhD Student Scholarship SFRH/BD/25368/2005 from the Portuguese FCT POCTI programme.

The authors are with the Institute for Systems and Robotics, Instituto Superior Técnico, Av. Rovisco Pais, 1, 1049-001, Lisbon, Portugal {marcomorgado,pjcro,cjs}@isr.ist.utl.pt

of the acoustic waves on the array receivers, the best achievable navigation performance from the inertial sensors, at affordable cost, and bearing the valuable knowledge inherent to the assembly and design of such a system. A similar design was presented in [7], in which the vehicle navigates underwater using an INS and surfaces sporadically to get Global Positioning System (GPS) position fixes and correct the errors of the INS.

The paper is organized as follows: Section II details the systems being developed which include an integrated USBL/INS system and a transponder. Section III describes the acoustic signaling techniques that are used and provides preliminary experimental results with the acoustic system developed in-house. Finally Section IV provides some concluding remarks on the work done so far and details the steps to be taken towards the final prototype, including planned extensive sea trials.

II. System design and description

The proposed USBL/INS hardware and software architecture consists mainly of two major standalone systems: the first is itself the ensemble between the acoustic array and the inertial unit, and all the workhorse that provides power signal acquisition and processing. The latter is a transponder that scouts for signals sent by the USBL array and replies after a previously stipulated elapsed time, so that the array can compute Round-Trip-Times (RTT) to the transponder. In this section all proposed systems and signal processing techniques are brought to full detail.

A. USBL/INS System overview

The integrated USBL/INS hardware is housed in an aluminum pressure tube capable of withstanding pressures up to 600 meters (tested on a water pressure chamber). The USBL array is built using Bosch-Rexroth aluminum rods and connections, which allows a highly configurable array structure, for optimal design during the evaluation and testing phases. The array is composed of 4 hydrophones placed in a non-planar configuration (that allows for 3D transponder localization) and is coupled to the aluminum pressure tube using a specially designed coupling device machined in high-resistant plastic.

Housed inside the system tube, a D.SignT Digital Signal Processor (DSP) package provides the main processing power of the system that performs: i) acoustic signal detection using high-speed Fast Fourier Transforms (FFT), ii) generates interrogation signals to the transponder using Pulse-Width-Modulation (PWM), iii) provides system data logging, and iv) an Ethernet interface to a console computer (which is used only for system configuration, system status checks and data de-logging). The power is provided by a 3700mAh 11.1V Lithium Polymer (LiPo) battery and a bank of DC-DC converters allowing for an estimated over four hour system autonomy, if used as a standalone system. When coupled to an underwater robotic vehicle, power can be supplied from the vehicle's own power and the Ethernet interface becomes available for data communications with the vehicle's control systems.

The main system blocks are depicted in Figure 2. The processor is a Texas Instruments C6713 floating point DSP and the acoustic signal acquisition is performed by a D.SignT ADDA16 card which provides four 16 bit synchronous acquisition channels with 250 KSPS (Kilo Samples Per Second) each. This acquisition card is connected to four Automatic Gain Control (AGC) signal amplifiers, whose gain can either be let in automatic mode or overridden by an analogue voltage control, from an Digital-Analogic Converter (DAC) also available on the DSP module. The receiving amplifiers are fine-tuned to operate on the band of 20-30 KHz.

To interrogate the transponder, the DSP card generates PWM (with an update rate of 250KHz and a resolution of 1/200 levels of PWM) through a FPGA that drives the emission power amplifier and an underwater acoustic transducer. The power amplifier and acoustic transducer system are also fine-tuned to transmit maximum energy on the band of 20-30 KHz. The signaling techniques will be further detailed in Section III.

A micro-controller card (designed in ISR) and a bank of 12 synchronous 24 bit high-performance Sigma-Delta AD converters provide the sampling capabilities of the IMU. From this AD converters bank, nine of the channels sample the triads of accelerometers, rate gyros, and magnetometers that constitute the IMU, whereas the other 3 channels provide supply voltage and accelerometer casing temperature sampling for best performance achievement. Sampling rates of up to 150 Hz can be selected, without loss of performance. A RS-232 serial link, with a baud rate of 115200 bps, is the interface between the DSP module and the micro-controller.

The IMU is pictured in Figure 3 where the triad of rate gyros can be seen on the left of aluminum frame, and the accelerometers triad housed inside the black casing. This frame also supports over the accelerometer casing the flux-gate magnetometer triad. This unit was previously tested in other ISR system and has thoroughly undergone several validation tests. The calibration of the IMU is also performed in ISR using a high-performance calibration table. The unit depicted in Fig. 3 in particular uses a Crossbow CXL10TG3 triaxial accelerometer, three Silicon Sensing Systems CRS03 rate gyros, and the Crossbow CXM113 triaxial flux-gate magnetometer.

In a general overview the system works as follows: the micro-controller collects data from the IMU and sends it to the DSP via the RS-232 serial link. The RS-232 interface on the DSP itself is receiving the data and storing it in memory using Direct Memory Access (DMA) controllers and without interrupting the core processor which is doing time-critical acoustic signal processing. The DSP processes this data when possible at non critical time-points.

At pre-specified instants of time (e.g. once a second), the DSP occasionally sends out a ping to the transponder and turns on the receiving subsystem to listen for the replies. After several pings and replies, and based on several factors like vehicle maximum speed, underwater sound speed and others, the DSP starts closing the listening time-windows to improve multi-path rejection. If replies from the transponder eventually get lost, the DSP rolls back to a fully open time search window until it gets a lock again.

The signal detection subsystem operates on a two-level scheme: the first called raw-detection is time-critical and

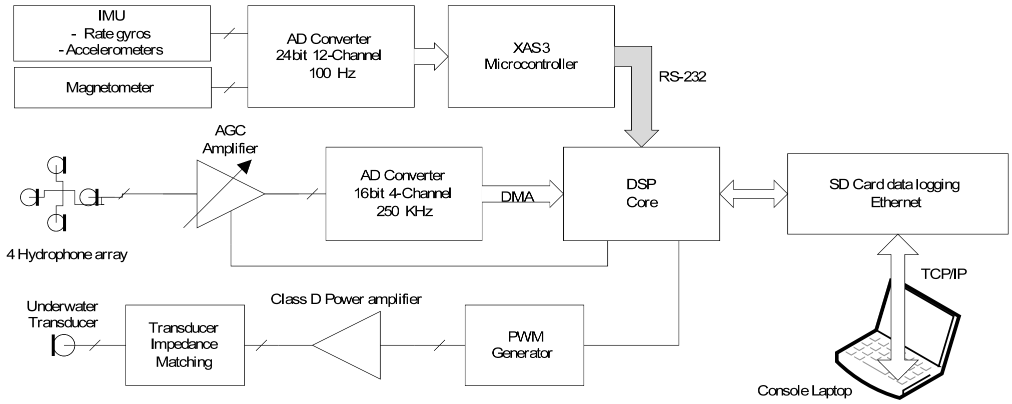

Fig. 2. Integrated USBL/INS system diagram

uses fast computations on the input signal to comply with the speed at which the signal is updated at the inputs. This phase does the processing on one single predefined channel while storing all the data for all channels on memory. This raw-detection schemes operates using matched-filters of the expected signal based FFT's and Overlap-Add convolution mechanisms, as illustrated in Figure 5.

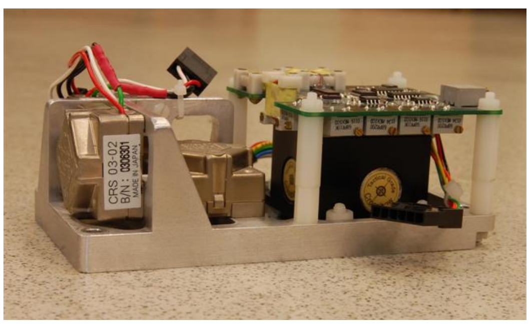

Fig. 3. Inertial Measurement Unit and Magnetometer support frame

Upon a correct detection of the signal in one channel, the signal is guaranteed by the detection scheme to be fully available on all channels, and then the listening subsystem is turned off and a fine-detection scheme is performed on all channels to get the Time-Of-Arrival (TOA) of the signal at each hydrophone.

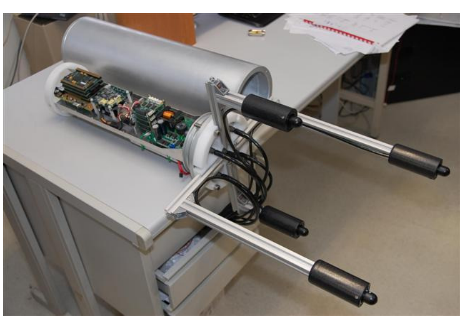

Fig. 4. Prototype system under development: acoustic array and core processing systems

The prototype under development is depicted in Figure 4, where the acoustic array and the core reception and IMU processing systems can be seen attached to one of the covers of the pressure housing aluminum tube.

B. Transponder system overview

The best way to describe the design of the transponder system is to simply put it has a subset of the previously integrated USBL/INS system described in Section II-A. The transponder system has to listen for ping requests sent by the USBL/INS system and reply to them with a predefined signal after a predefined interval of time. For this purpose, the transponder only needs a receiving channel and does not need the IMU and the Micro-controller to interface it.

Thus, the transponder system inherits from the previously described system the following blocks: the DSP with the acoustic acquisition card and the PWM generator, one AGC amplifier, the emission power amplifier, battery and bank of DC converters and one acoustic transducer that serves has a receiving hydrophone and as transmitting transducer. Additional electronics are also added for coupling the transmitting and receiving circuits to the same acoustic transducer to avoid the appearance of high transmission voltages at the receiving AD converters when replying to the ping requests.

III. ACOUSTIC SIGNALING TECHNIQUES

This section presents some background and remarks on acoustic signaling techniques with application to underwater range measurements. Although simulation results have naturally driven the development presented herein, we directly validate the theoretical background with experimental results with an array of two hydrophones and one transmitter.

A. Background

The opacity (i.e. high attenuation) of the ocean environment to most electromagnetic signals makes acoustic propagation the preferable method to obtain practical range measurements. Acoustic signals have been used for precise underwater range measurement by time-of-flight of acoustic waves in the last decades [8]. Historically, due to the simplicity of the hardware involved, sinusoidal pulses were the primordial choice for underwater range measurements. Recent advances and the availability of low-cost, high-speed Digital Signal Processors (DSP) hardware and software, amplifiers and wide band acoustic transducers allow for the use of more advanced signaling techniques like CHIRP tone bursts and spread-spectrum signals [9], [10]. In general, spread-spectrum signals have several advantages when compared to conventional signaling for underwater range estimation: they present better Signal-to-Noise-Ratio (SNR), robustness

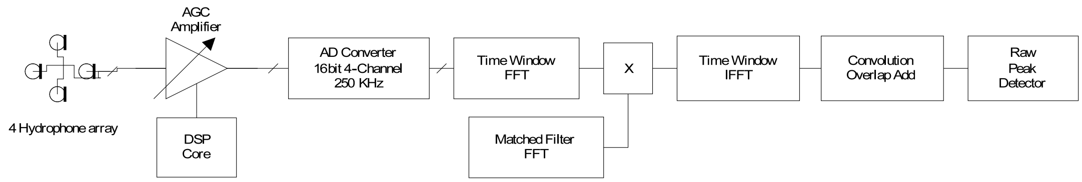

Fig. 5. Raw detection scheme

to ambient and jamming noise, multi-user capabilities, improved detection jitter, and the ability to better resolve multipath which is one of the biggest problems in underwater channel acoustic propagation.

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. 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 [11] 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 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 the scope of this work, we focus our attention on DSSS modulated signals and its performance as an acoustic ranging signal compared to conventional approaches using sinusoidal pulses and CHIRP tone bursts. Closely related work can be found in [9], [10], and in [12].

B. Preliminary harbor experimental tests

Preliminary experimental trials were conducted in a harbor, in Sesimbra - Portugal, to assess the feasibility of the acoustic ranging system to be developed. In these tests, a receiving array of 2 hydrophones placed 20 cm apart was fixed to the pier at about 2.5 meters deep. The transmitter was placed in several locations in the field of view of the array so that we could test several distances and angles of arrival at the receiver, also placed at about 2.5 meters deep on each transmission location. The underwater sound speed was about 1514 meters per second as measured by a Sound Velocity Profiler (property of ISR). An aerial view of Sesimbra's Marina is depicted in Figure 6, where the receiving array position and the transmitter locations are illustrated. Several boats were floating inside the marina besides the floating piers, and combined with a maximum depth of 9 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.

To test the feasibility of the acoustic ranging system, the transmission and reception were performed using the hardware to be used in our prototype system, and synchronized with GPS PPS clock with a precision of $1\mu s$. We transmitted from all the locations several signals from which we select three in this paper: a $5.08ms$ sinusoidal pulse, a $5.08ms$ CHIRP tone burst from 20KHz to 30KHz, and a DSSS modulated signal. To generated the DSSS signal, a 127 chips Gold Code was used to BPSK modulate a $25KHz$ carrier signal. All signals were generated using the PWM generation scheme described previously. The signals were recorded for post processing using the reception amplifiers set to a fixed gain so that we could mimic some Signal-to-Noise-Ratio (SNR) scenarios by varying the distance of the transmitter.

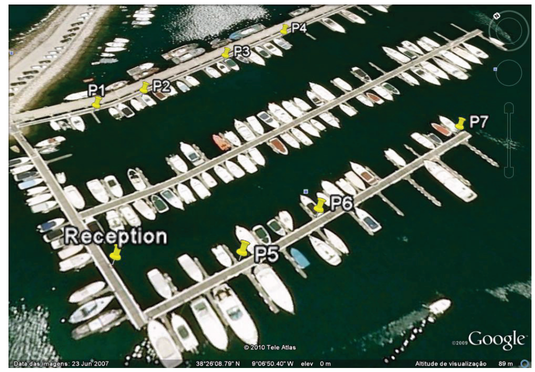

Fig. 6. Aerial view of Sesimbra's Marina (preliminary acoustic harbor trials)

In these tests we did not seek to study the effects of code length on the performance of the system nor absolute precision of the measured distances and angles. Instead we tested for system repeatability and robustness from several trials at fixed locations - eight trials for each signal and each location. As convincingly argued and demonstrated in [10], longer codes provide better ranging performance. Given the amplifier size, bandwidth and power constraints, the choice of code length used in these tests seems appropriate. A code length / performance analysis of the acoustic ranging system will be conducted in the near future.

The distance from the transmitter to each of the receivers is thus calculated by multiplying the time-of-flight (between the transmitter and each receiver) by the underwater sound speed. The angles are calculated using a planar wave approximation and depend directly on the local sound speed. Thus, the angle of arrival θ at the array is computed as

$$\theta = \arcsin(\frac{\tau \times v_s}{d}) \qquad (1)$$

where τ is the Time-Difference-Of-Arrival (TDOA) between the two channels, v_s is the underwater sound speed, and d is the distance between the two receivers on the array.

To compute the TDOA τ we use two distinct methods. The first, which we call direct method, is processed by separately computing the Time-Of-Arrival (TOA) of the signal at each channel and then subtracting the TOA of channel one from the TOA of channel two. The latter method, which we call cross method, is accomplished by first interpolating both channels from the sampling frequency of 250KHz to 1MHz, since we know that the input signal is band-limited, to get better resolution. Then we search at which receiver the signal arrived first and select a slice from that channel around the detected TOA to make a new matched-filter. Taking into account enough margins for TOA detection errors and for the maximum possible TDOA between the two channels, this new matched-filter is applied to the same time slice on the other channel. This method gives some robustness to the system if one of the TOA occurs much later due to a poor detection on that particular channel. We claim that under SNRs higher than 1, this method allows for a better measurement of the TDOA. For small SNR scenarios, this method might not give accurate results since a noise source that is emitting from approximately the same direction of the source might mislead the detector. For the trials conducted in these tests, the SNR was above 1 for every transmitting position.

Due to the overwhelming amount of data available from all the trials, we try to show in this section the most significant results and comparisons that help leading to satisfactory conclusions. To show the clear improvement on the sharpness of the output of the matched filter by using the spread-spectrum signal, we compare the matched filter output of one single channel on one trial from Position number 3. Figure 7 overlaps the envelope of the output of the three matched filters, where we can see that the output of the sinusoidal pulse is not very sharp not allowing for a confident decision and computation of the arrival time. The envelope of the CHIRP tone burst matched-filter shows already an improvement on the sharpness of the output, whilst the clear improvement is, as expected, evidenced by the sharpness of the matched-filter of the DSSS modulated signal.

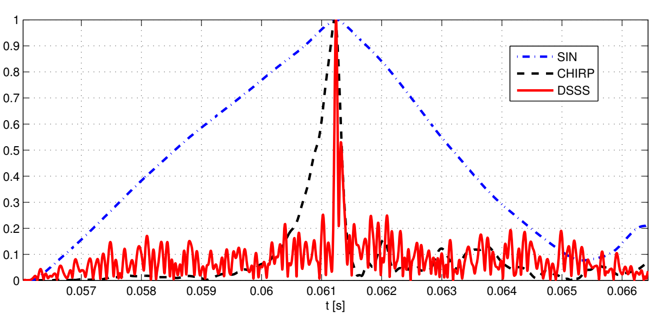

Fig. 7. Matched Filter output envelope

To overview the repeatability of the detection system in calculating the Angles-Of-Arrival (AOA), we present pairs of mean and standard deviation (Std) for the 8 trials at each position and signal, for the direct method and for the cross method, respectively in Tables I and II. The distances measured on channel one are also presented in Table III to assess the ranging capabilities of the system. The approximate distances and angles between the transmission locations and the receiving array, as measured using Google Earth, are also detailed in each respective Table.

Analyzing the results presented in Tables I-III, we can see that in general the distances measured on channel one are well within the expected values considering the testing conditions (oscillating floating piers, flexible transmitter cables, ocean currents, and other factors). The results of the angle computation using the direct method are very discouraging, contradicting somehow what was expected. This can be explained by the fact that the signal that we have for use as a matched-filter in detecting was the theoretically expected signal. We noticed that the use of this signal is fair enough for a raw detection of the signal in the water as to get a good idea of where the signal is. As for a fine detection possible scheme, the cross method showed that we can get very good results (for favorable SNR scenarios) if we seek to use the detected signal in one channel to measure the TDOA on the other channel.

An analysis of the amplitude of the signals showed that the amplitude decreased to about half from an increase of distance with a factor of about 3,75. Given that the test site was very shallow and far from ideal, this amplitude reduction can not be explained by simple theoretical models like radial propagation. From the results it was also possible to evidence that the CHIRP signal propagated more energy in the water, about five times the amplitude of the DSSS signals, however this is also related to the way the emission amplifiers were designed and respond to the different types of phase/frequency modulation. This comparison was done using fixed emission and reception gains, which leaves for further improvement by selecting higher gains if DSSS signals are used. Interestingly enough, from the results it was possible to verify that the increase of distance did not reflect in a degradation of the matched filter response.

To illustrate the output of the cross method in which the signals are sliced and interpolated to be cross-correlated between the two receiving channels we present the envelope of the output of the matched filter for the cross method for the CHIRP tone burst and the DSSS modulated signal in Figure 8. Notice that as this method serves to measure the TDOA between the two receivers, the time reference on these plots are related to a common point from which the signals were sliced and are not synchronized with the GPS clock. We can see from the plot that width of the main lobe of the matched filter output envelope for the DSSS coded signal is about half the size compared to the case of the CHIRP tone burst, which reflects on a more robust detection of the main peak.

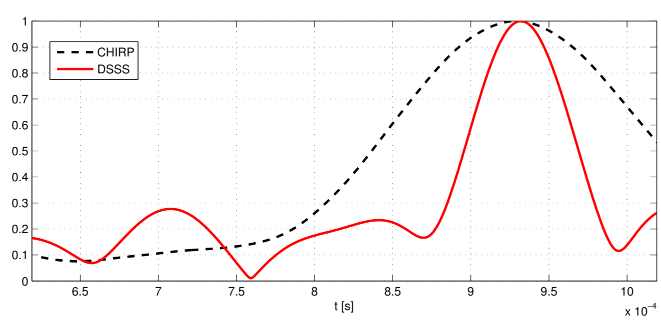

Fig. 8. Matched filter output envelope of Channel 1 slice upsampled and crossed on Channel 2

In a general overview, we can see that the CHIRP burst

TABLE I

ANGLES COMPUTATION USING THE DIRECT METHOD - PAIRS OF (MEAN / STD) - IN DEGREES

	Position						
Signal	1	2	3	4	5	6	7
SIN	-9.4 / 87.6	64.8 / 15.6	32.5 / 10.3	31.8 / 28.1	-19.7 / 52.8	-27.6 / 62.1	-4.6 / 9.6
CHIRP	68.7 / 2.1	70.9 / 22.0	45.9 / 11.9	41.5 / 11.2	-32.5 / 11.7	-3.1 / 11.6	-11.6 / 12.7
DSSS	69.3 / 1.6	73.6 / 17.6	39.5 / 1.2	30.2 / 1.0	-32.3 / 1.1	-19.0 / 0.8	-10.7 / 0.6
Expected θ	70.1	56.8	38.9	30.2	-33.3	-20.9	-12.9

TABLE II

ANGLES COMPUTATION USING THE CHANNEL CROSS METHOD - PAIRS OF (MEAN / STD) - IN DEGREES

	Position						
Signal	1	2	3	4	5	6	7
SIN	16.9 / 47.5	22.8 / 9.9	13.0 / 9.2	13.7 / 6.6	-15.5 / 12.2	-12.4 / 13.8	-9.0 / 6.3
CHIRP	68.6 / 0.0	56.6 / 0.4	38.9 / 0.0	30.5 / 0.3	-32.2 / 0.4	-18.8 / 0.4	-11.1 / 0.5
DSSS	69.2 / 0.7	56.4 / 0.0	39.1 / 0.3	30.7 / 0.4	-32.1 / 0.7	-19.0 / 0.5	-10.8 / 0.5
Expected θ	70.1	56.8	38.9	30.2	-33.3	-20.9	-12.9

TABLE III

DISTANCE MEASUREMENTS TO RECEIVER 1 - PAIRS OF (MEAN / STD) - IN METERS

	Position						
Signal	1	2	3	4	5	6	7
SIN	58.69 / 2.58	64.2 / 0.12	85.24 / 0.12	105.66 / 0.24	28.21 / 0.27	48.63 / 0.14	100.1 / 0.11
CHIRP	56.9 / 0.14	64.13 / 0.12	85.14 / 0.11	105.59 / 0.25	28.05 / 0.15	48.59 / 0.12	100.0 / 0.13
DSSS	56.97 / 0.14	64.16 / 0.11	85.18 / 0.13	105.59 / 0.24	28.05 / 0.17	48.59 / 0.13	100.03 / 0.11
Exp. Distance	56.3	62.1	83.0	103.3	27.5	48.3	99.4

tones yielded the same angle and distance precision as the DSSS modulated signal. However, due to the evidenced improved sharpness of the output of the matched-filter, and other important factors like multi-user capabilities with good cross-correlation properties, we are keen to choose the DSSS signals over the CHIRP tone bursts. Given the test conditions, the results presented so far are satisfactory and decisive, not precluding however future improvements and developments on the detection schemes in the near future.

IV. CONCLUSIONS AND PLANNED SEA TRIALS

The design of an integrated USBL/INS system and a transponder was presented and discussed. This design aims at building a low-cost navigation system with application to marine robotic vehicles. Preliminary harbor tests with experimental data were presented to validate the usage of spread-spectrum coded signals for the acoustic positioning device, leading to satisfactory results so far. Even thought further improvements on the acoustic detection mechanisms are desirable and will be one of the main focus in the near future. The assessment of the overall attainable performance of the full navigation system and comparison with currently available commercial solutions, still requires extensive sea trials, which are planned for the upcoming months.

V. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of Manuel Rufino, Bruno Cardeira, Luis Sebastião, Pedro Serra, João Oliveira, and João Botelho throughout the development of the prototype and the preliminary sea trials.

REFERENCES

[1] L. L. Whitcomb, “Underwater robotics: out of the research laboratory and into the field,” in *Robotics and Automation, 2000. Proceedings. ICRA ’00. IEEE International Conference on*, vol. 1, 2000, pp. 709–716 vol.1.

[2] A. Pascoal, P. Oliveira, and C. Silvestre *et al.*, “Robotic Ocean Vehicles for Marine Science Applications: the European ASIMOV Project,” in *Proceedings of the Oceans 2000*, Rhode Island, USA, September 2000.

[3] M. Morgado, P. Oliveira, C. Silvestre, and J. Vasconcelos, “USBL/INS Tightly-Coupled Integration Technique for Underwater Vehicles,” in *Proceedings Of The 9th International Conference on Information Fusion*. Florence, Italy: IEEE, July 2006.

[4] M. Morgado, P. Oliveira, and C. Silvestre, “Posterior Cramér-Rao bounds analysis for INS/USBL navigation systems,” in *Proceedings Of The 8th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC 2009)*. São Paulo, Brasil: IFAC, September 2009.

[5] M. Morgado, P. Oliveira, C. Silvestre, and J. Vasconcelos, “Vehicle Dynamics Aiding Technique for USBL/INS Underwater Navigation System,” in *Proceedings Of The IFAC Conference on Control Applications in Marine Systems*. Bol, Croatia: IFAC, September 2007.

[6] ——, “Improving Aiding techniques for USBL Tightly-Coupled Inertial Navigation System,” in *Proceedings Of The IFAC World Congress 2008*. Seoul, South Korea: IFAC, July 2008.

[7] X. Yun, E. Bachmann, R. McGhee, R. Whalen, R. Roberts, R. Knapp, A. Healey, and M. Zyda, “Testing and evaluation of an integrated gps/ins system for small auv navigation,” *IEEE Journal of Oceanic Engineering*, vol. 24, no. 3, pp. 396–404, 1999.

[8] P. Milne, *Underwater Acoustic Positioning Systems*. Gulf Pub. Co., 1983.

[9] T. Austin, “The application of spread spectrum signaling techniques to underwater acoustic navigation,” in *Proceedings of the 1994 Symposium on Autonomous Underwater Vehicle Technology, 1994. AUV ’94*, 1994.

[10] B. Bingham, B. Blair, and D. Mindell, “On the design of direct sequence spread-spectrum signaling for range estimation,” in *OCEANS 2007*, 2007, pp. 1–7.

[11] D. V. Sarwate and M. B. Pursley, “Crosscorrelation properties of pseudorandom and related sequences,” vol. 68, no. 5, 1980, pp. 593–619.

[12] B. Bingham, D. Mindell, and T. Wilcox, “Integrating sharps ii precision navigation into jason/medea two-vehicle operation,” in *OCEANS, 2005. Proceedings of MTS/IEEE*, 2005, pp. 1603–1609 Vol. 2.