Preliminary Results from Project MAST/AM-Advanced Tracking and Telemetry Methodologies to Study Marine Animals

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***Abstract* - This paper proposes advanced methodologies for the study of tagged marine animals, resorting to telemetry techniques. The robotic tools to be developed and operated will be able to track the acoustic signals emitted by the animals, based on range and depth data acquired with ultra-short baseline positioning (USBL) systems aided Inertial Navigation Systems (INS). The USBL is composed of an array of hydrophones with a pre-specified structure and the INS is based on the numerically integrated measurements from triads of low cost accelerometers, rate-gyroscopes, and magnetometers, complemented with data from depth cells. The preliminary design and implementation phases will be described and the results obtained to validate the proposed approach will be presented. Finally, the next development and validation phases will be briefly outlined.**

I. INTRODUCTION

With the recent advances in technology, telemetry is playing an ever more important role in marine biology [HM06]. Decreasing size of transmitters along with increasing reliability of equipment has resulted in applications with smaller species [MC07], in salt or brackish water. Acoustic based telemetry can provide important knowledge on marine animals daily movement patterns and behavior [ZD99, SJ01, JC02, HM06, AD08], migration patterns in marine protected areas [ZD99], comparative behavior of wild and cultured fish [LP09], habitat use [FE09], and data for defining essential fish habitat [PS04]. These studies on marine animal behavior are instrumental to validate and solve a number of challenging problems in marine biology, as they complement other marine telemetry methods such as pop-up satellite archival tags [BB01a, BB01b].

Acoustic telemetry systems [KD00] consist of combinations of transmitters and active or passive receivers. Acoustic transmitters produce continuous or coded omnidirectional signals that can contain the identification of the animal or information from installed sensors [e.g pressure/depth, temperature, and water pH level). A number of brands of transmitter are available, including: Vemco: 69kHz, 7 to 16mm diameter, equipped with temperature, pressure and accelerometer sensors, Lotek: 76 and 200kHz, with movement, temperature and pressure sensors, Sonotronic series CT: 69 kHz and three other frequencies, series CTT: temperature sensor, Hydroacoustic technology: Model 795, 307kHz and Thelma: 69 kHz, with pressure, dissolved oxygen, ECG, accelerometer, conductivity and temperature sensors.

Both active and passive acoustic telemetry is possible, with the former allowing real time tracking and monitoring using omnidirectional and/or directional hydrophones, with approximate location of the tagged individuals depending largely on user experience and environmental conditions (in the order of tens of meters of accuracy). Passive telemetry makes use of fixed hydrophones deployed for long periods. Passive telemetry receivers consist of a receiver and omnidirectional, directional or multi-element hydrophones, a data storage system, and battery. The VR100 (Vemco), MAP 600 Receiver (Lotek), ManTrack and USR-08 Ultrosonic Receiver (Sonotronics), and Model 290 Acoustic Tag Receiver (Hydroacoustic technology) are considered as state of the art solutions.

Passive receivers include an omnidirectional hydrophone, a data storage system, and battery. Currently, VEMCO has the VR2W and VR3-UWM models operating at 69kHz, Lotek the WHS2000 and 3000 and Sonotronics the SUR-1 system. These systems use up to 69 KHz and are compatible with transmitters of various brands. When using several passive receivers in a specific area, some of these systems allow for signal positioning derived by triangulation, thus providing localization estimates with considerably higher accuracy (few meters compared to tens of meters). Yet, such output is often too laborious and expensive due to the large amount of receivers involved.

The goal of the project “Advanced Tracking and Telemetry Methodologies to Study Marine Animals – MAST/AM,” funded by the Portuguese Science Foundation, is to endow the scientific community with new moderate cost robotic tools able to track multiple tagged marine animals supported on ultra-short baseline positioning (USBL) aided inertial navigation systems (INS) systems. The goal is to provide estimates on the trajectories of the multiple targets at rates of 1Hz to1/5 Hz,

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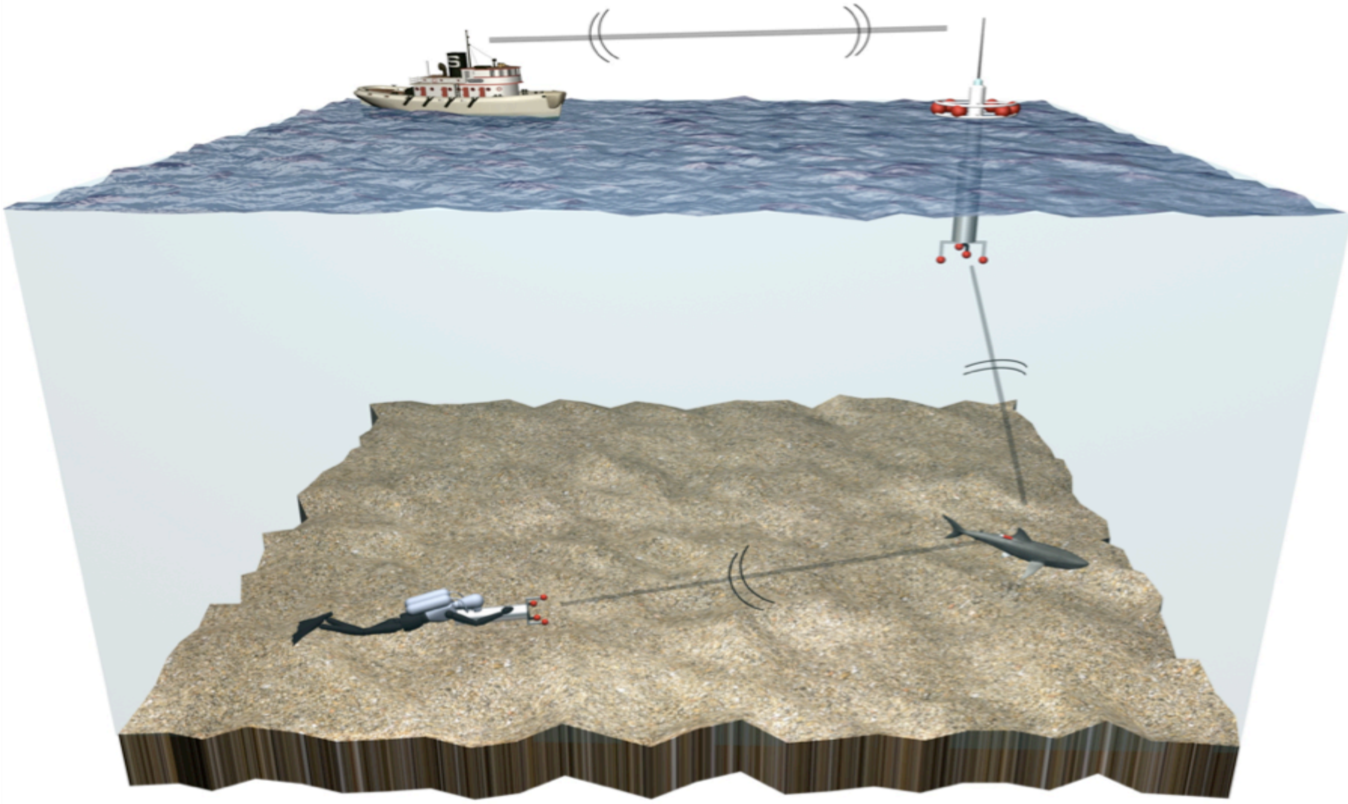

Figure 1. MAST/AM mission scenario.

with metric accuracy during the sea missions and sub-metric accuracy after post-processing, from low rate (1/30 Hz to 1/90 Hz) acoustic data emitted from commercially available tags and from high data rate (100 Hz) measurements from inertial MEMS sensors, installed onboard the robotic tools. Furthermore, resorting to (sub-) optimal nonlinear estimation techniques [MM08, MM09] sub-metric accuracy would be achieved in post-processing. These new methodologies are based on USBL aided INS systems to be detailed in the remainder of the paper.

II. Mission Scenarios and Tools Development

Under the framework of the current project, several marine robotic tools will be designed, developed, and tested in a number of sea trials with increasing complexity. The implementation of those equipments builds mainly on previous know-how and experience of the team [MM09, VP11]. First the prototypes will be tested in the laboratory, then preliminary tests will be carried out at sea, and at a later stage the equipment will be made fully operational, for use in extended periods of time. Some of the envisioned missions and the robotic tools to be developed and operated are described next.

Marine Robotic Tools

The following marine robotic tools are under development and will constitute the solution for the tracking and telemetry problems at hand:

a) SURFACE ROBOTIC TOOL - Long term Surface Buoy with USBL aided INS composed by: Solar panel and batteries, GPS receiver, UHF radio modem and aerial antenna, USBL array (hydrophones/underwater transducers), inertial measurement unit (triads of accelerometers, rate gyros, and magnetometer), digital signal processing (DSP) board with sampling and communication capabilities, installed in a marinised aluminum metallic container.

b) PORTABLE TOOL - Portable Underwater Robotic Tool with USBL aided INS navigation system composed by: Batteries, USBL array, inertial measurement unit, DSP board able of sampling the sensor package, logging capabilities, installed in a miniature marinised neutrally buoyant aluminum metallic container.

c) OPERATION CONSOLE – consisting of a portable PC and a UHF radio, to be installed in a scientific laboratory on shore or on a support vessel [PA06].

Mission Scenarios

The Robotic Tools will be designed mainly by the Engineering team of IST and will be validated in sea missions with augmenting degree of risk and complexity, involving several resources and strategies defined by the team of Marine Biologists of CCMAR, in close collaboration with the colleagues from HMS-Stanford and DPAq-UFRPE. An artist's view of the paradigm to be implemented is depicted in Fig. 1 and is detailed in the following three sets of mission scenarios:

1) Installation of a SURFACE ROBOTIC TOOL (SRT) including an USBL aided INS system, energy sources, GPS receiver, and UHF communication modems, able to monitor an area. Examples of missions: i) detection and identification of an acoustic tag, moored at the sea bottom, ii) range and accuracy tests (e.g mooring a tag and move the SRT, with the help of a small ship), iii) independent sound wave velocity test, resorting to pre-calibrated moored tag, iv) multi-tag mission, carried out by SCUBA divers in a pre-specified mission, and v) presence of one or more tagged marine animals (captive and free).

2) Simulated situations where the scientists receive reports from the SRT on the number of animals present, the identification codes, telemetry data, and full 3D trajectories. Studies on detection success (false negatives/missing rates), distance and sea disturbances impact. Alarm and warning generation tests from the SRT to the monitoring station.

3) Use of the PORTABLE UNDERWATER TOOL to provide an estimate of the target trajectory, helping the SCUBA diver to find tagged marine animals and equipment. The tool is also composed of a USBL aided INS system, with the capability of emitting a specific signal that allows the surface craft to track the diving operation. Preliminary tests with one fixed tag in the bottom, with a human SCUBA diver carrying the tag in a pre-specified trajectory, and with one or more marine animals will be conducted.

The desired specifications for these robotic tools are: periods of operation (weeks for the surface system, 3-4 hours for the underwater unit), range of operation (600 to 1000 meters), accuracy of the system (1-2 m of error on the 3D marine animal position estimate), and rates on the trajectory estimates (1 to 5 sec typ.). Given the robotic tools available and the mission scenarios selected a number of warnings (e.g. detection of new animals, threshold on the count of simultaneous animals, low power on the system,…) and alarms (e.g. presence of a specific animal, long immobilization of animals, maintenance required, malfunction of subsystems,…) will be proposed.

At the core of the robotic tools to be developed is the development of inertial navigation systems (INS). The design and use of such systems for underwater and aerospace applications has been a major challenge since their early development in the middle of the last century, at the Charles Draper Laboratory, MIT [VJ11]. In recent years, low-cost INS systems stepped forward as a significant aid for Underwater Vehicles (UV) navigation to fulfill several missions at sea [AA07, MM08]. The execution of these tasks, that include environmental monitoring, surveillance, underwater inspection of estuaries, harbors, and pipelines, and geological and biological surveys, requires low cost, compact, high performance, and robust navigation systems that can accurately estimate the UV position and attitude. The inputs to the navigation systems are the high data rate measurements provided by inertial sensors (accelerometers and rate-gyroscopes), complemented with data from magnetometers [VP11], depth cells, accelerometers [BP11], Doppler velocity logs, and optical gyroscopes (RLGs and FOGs), see [MM09, VJ11] and references therein. The algorithms implemented are rooted on the open loop numerical integration (or double integration) of the compensated measurements from the sensor suite. Although the INS system yields excellent short-term accuracy, long-term position drifts arise due to the integration of non-ideal inertial sensors bias and noise, if not compensated by aiding sensors. To help improve the INS performance (e.g. to metric accuracy), one possible approach is to include low data rate measurements from Ultra-short Baseline (USBL) underwater positioning systems [AA07, MM09].

III. USBL/INS DESIGN

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 the workhorse that provides power signal acquisition and computer processing. The latter is the acoustic tag installed in the marine animals. The tags emit signals periodically, at a pre-programmed rate. The hydrophone array can compute the direction to the acoustic tags.

The integrated USBL/INS hardware is housed in an aluminum pressure tube capable of withstanding pressures up to 600 meters (tested in a water pressure chamber). The USBL array is built using Bosch-Rexroth aluminum rods and connections, which allows for 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) provides system data logging, and iii) an Ethernet interface to a console computer (which is used only for system configuration, system

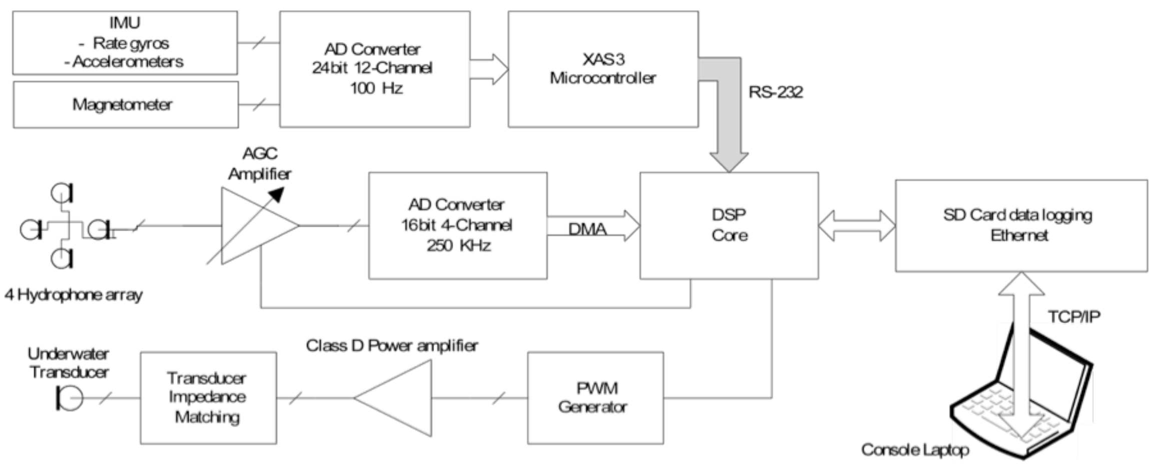

Figure 2. Integrated USBL/INS system diagra.m

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 Fig. 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 16bit 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.

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 Fig. 3 where the triad of rate gyros can be seen on the left of the 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 systems and has undergone several thorough 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.

The signal detection subsystem operates on a two-level scheme: the first, called raw-detection is time-critical and 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 scheme operates using matched-filters of the expected signal based on FFT's and Overlap-Add convolution mechanisms.

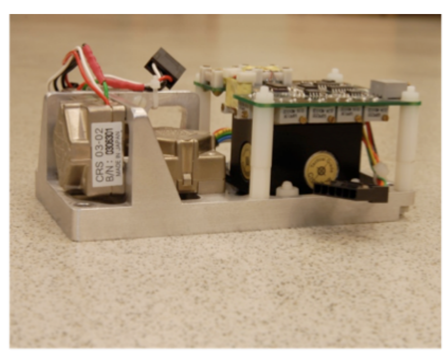

Figure 3. Inertial Measurement Unit and Magnetometer support frame.

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 incoming signal direction.

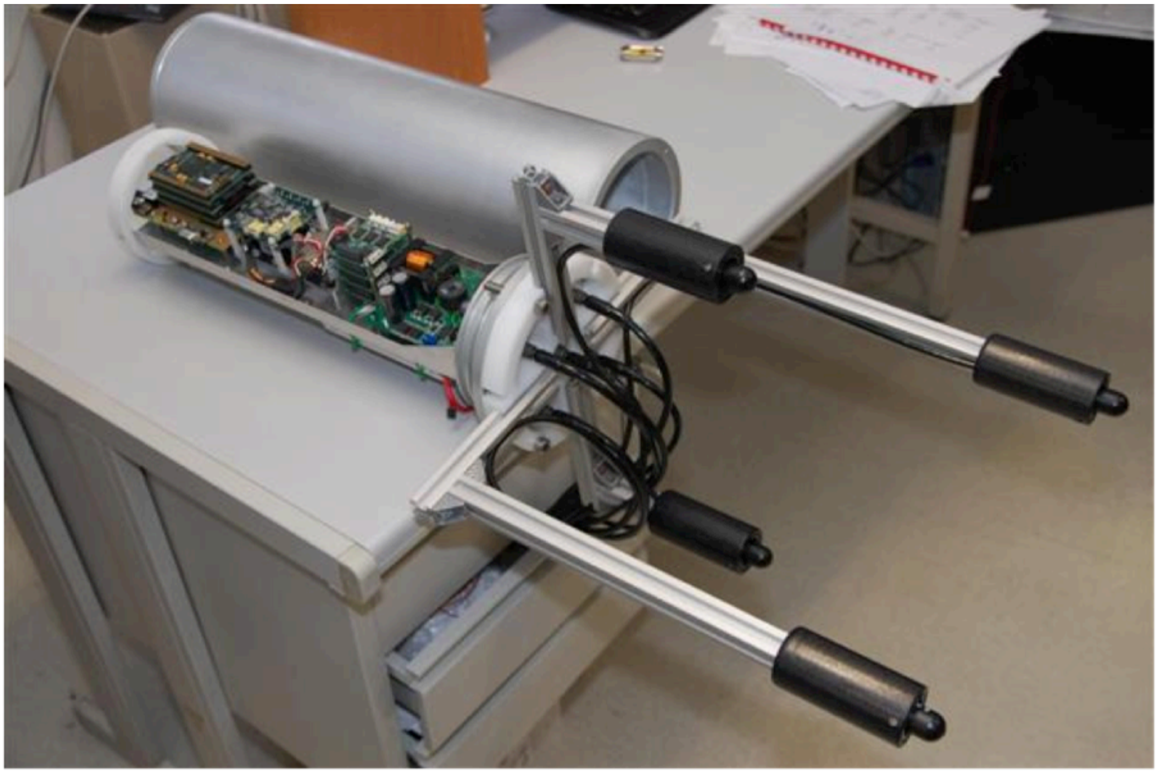

Figure 4. USBL/INS prototype under development.

After several pings are detected, 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 the signal from the acoustic tag eventually gets lost, the DSP rolls back to a fully open time search window until it gets a lock again.

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

The development of this unit is complemented with recent theoretical results that pave the way for the use of USBL/INS systems, namely:

i) the study on the observability of the INS/USBL system in the presence of reduced aid from the exterior is a subject of great interest. Inspired by recent results obtained by the team in [BP09, BP11], it is expected to find formal results on the configuration of the USBL array and on the trajectories that must be executed to be technically possible to estimate the unknown states.

ii) the performance attained by an USBL array aiding an INS was recently deduced [MM09], resorting to the Cramér Rao lower bound. The structure and nonlinear estimation techniques seems to be found in theory. To prepare for the validation of those results from sea data and the extension of those results to the case where low data rate from the USBL must be fused with high data rate inertial measurements is still a challenging and open problem. The study on the performance degradation when data is missing is a very important issue and must be studied in detail; and

iii) the improved results on navigation system design, when resorting to dynamical models of the underwater robots, [MM08, MM09], suggests that if marine animals movements can be characterized accurately then enhanced INS performance could be achieved [AA07].

IV. PRELIMINARY EXPERIMENTAL VALIDATION

This section reports the experimental evaluation of the proposed positioning methodologies with data acquired with the USBL/INS prototype just described. The sea trials were conducted inside a harbor, 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. The hardware and signal processing that was used in the harbor trials was briefly described [MM09] and consists of a small array of four hydrophones placed in a non-planar 3D configuration with a highly configurable geometry. The receiving acoustic array is depicted in Fig. 4 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 acoustic signals was placed around 21.5 meters away from the USBL, around 2 meters to the left and 2.5 meters deep, with both the transmission and reception synchronized with the GPS 1PPS clock with a precision of 1µs.

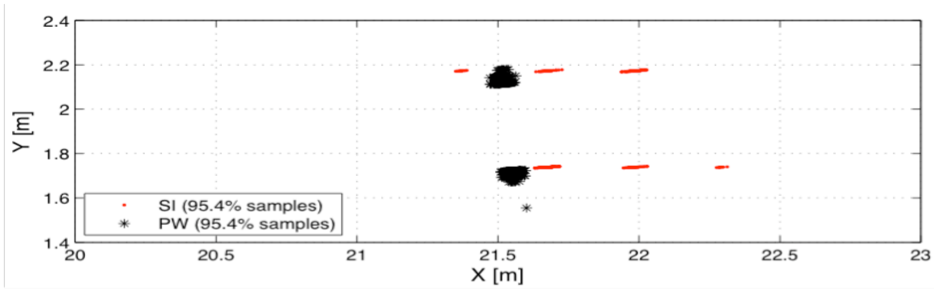

Figure 5. Positioning methods experimental validation: static position results.

A method of measuring the Time Differences of Arrival was proposed in [MM09], based on the cross-correlation between the acoustic signals acquired at all the receivers. The preliminary tests using two hydrophones placed horizontally 20 centimeters apart, revealed good performance for several types of modulation – pure sinusoids, chirp, and spread spectrum signals.

From the XY scatter in Fig. 5, it can be seen that the Planar Wave (PW) method (see [MM09] for details) revealed a smaller dispersion of position estimates compared to classical methods. The results obtained have an accuracy of about 1.36%, given the baseline of 0.3 cm with a slant-range of 21.5 m, thus paving the way for its application in tracking marine animals.

V. CONCLUSIONS

The development of the robotic tools, set forth in the project MAST/AM, has been pursued successfully during the last months. A prototype of the Surface Robotic Tool is almost finished and sea trials with commercially available miniature acoustic tags will be carried out in the near future. The Portable Underwater Robotic Tool will be developed during the last trimester of the present year. Those tools will endow the scientific community with instruments for the 3D real time tracking of tagged marine animals. Methodologies for post-processing the data acquired with these robotic tools will be developed in 2012, resulting in full 3D position and velocity trajectories with data rates and accuracies not possible with the current commercially available systems.

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