Development of a Portable Underwater Tool to Track Marine Animals

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Abstract **This work presents the design, implementation, and validation at sea of an USBL/INS acoustic positioning system. The architecture was implemented in a portable underwater tool capable of acquiring and processing acoustic signals transmitted undersea. From the signal acquisition and processing, the transmitter's position can be estimated. This architecture is supported on the fusion of data from an ultra-short baseline system (USBL), and an inertial navigation system (INS).**

It is noteworthy that the portable underwater tool was developed and tested in the scope of the "Advanced Tracking and Telemetry Methodologies to Study Marine Animals" (MAST/AM) project conducted in *Instituto de Sistemas e Robótica* (ISR) of *Instituto Superior Técnico* (IST),

I. Introduction

Worldwide, development of underwater vehicles has expanded to the point where they have become able to accurately survey large ocean areas. Routine operations such as surveillance, environmental monitoring and underwater inspection are nowadays tasks commonly performed either by remotely operated vehicles (ROVs) or by autonomous underwater vehicles (AUVs). The ability of reaching the deepness of the oceans and perform these procedures, often impossible or hazardous for humans, makes marine robotic tools emerge as one of the strongest focus of investigation and efforts by the robotics scientific community [4]. This, combined with advances in telemetry systems and the decreasing size of transmitters along with increasing reliability of equipment has resulted in the possibility for applications with smaller species, in salt or brackish water [6]. Acoustic based telemetry can provide important knowledge on the behavior of various types of marine animals, as the results of direct observation of their habitats, migrate patters, among others, are instrumental to validate and solve a number of challenging problems in marine biology.

Some of the most important concerns for underwater navigation are the effects of acoustic propagation. Electromagnetic energy cannot propagate appreciable distances in the ocean except at very low frequencies. Acoustic energy, however, propagates well in the ocean, and hence acoustic transponders are used to guide the motion of an underwater vehicle without the need for resurfacing. Acoustic transmitters produce continuous or coded omnidirectional signals that can contain the identification of the animal or information from installed sensors. The primary choice for underwater positioning often resides among systems such as long baseline (LBL), short baseline (SBL) and ultra-short baseline (USBL). The study of these systems is, thus, considerate to be of high importance for the implementation of underwater applications.

The use of these robotic platforms requires low-cost, compact, high performance robust navigation systems that can accurately estimate the vehicle's position and attitude. Navigation is an important requirement for any type of mobile robot, but this is especially true for autonomous underwater vehicles. Good navigation information is essential for safe operation and recovery of an underwater vehicle. For the data gathered by an underwater vehicle to be of value, the location from which the data has been acquired must be accurately known [3]. In fact, the design and implementation of navigation systems stands out as one of the most critical steps towards the successful operation of autonomous marine robotic vehicles. Inertial navigation systems (INSs) provide self-contained passive means for threedimensional positioning in open ocean with excellent short-term accuracy. Consequently, their study is considered essentially for a successfully underwater vehicles operation. However, unbounded positioning errors induced by the uncompensated rate gyro and accelerometer errors degrade the INS accuracy over time. Diverse techniques, such as an Extended Kalman Filter (EKF) combined with aiding devices, such as the magnetometer, are adopted to estimate and compensate the INS integration errors build-up.

The MAST/AM project addresses advanced methodologies for the study of tagged marine animals, resorting to telemetry techniques. It intends to develop and operate robotic tools able to track the acoustic signals emitted by marine animals, based on range and depth data acquired with an USBL system aided by an INS. Tracking can be engaged over considerable distances, ranging typically from a few meters to several kilometers. The USBL and INS systems are implemented within the underwater portable tool. Said tool is be carried by a diver (Fig. 1), who is able to perform tracking of the marine animal which emitted the signal.

Nowadays, tracking of marine animals is achieved through the insertion of a tag which acts as a transmitter of a known signal. This signal is acquired by a receiver and processed in order to obtain some information concerning the location of said marine animal. Regarding the production and sale of these products for emission and reception, one can state that the brand VEMCO© is the most acquired by the scientific community. One of the purposes of the MAST/AM project is for the signal acqui-

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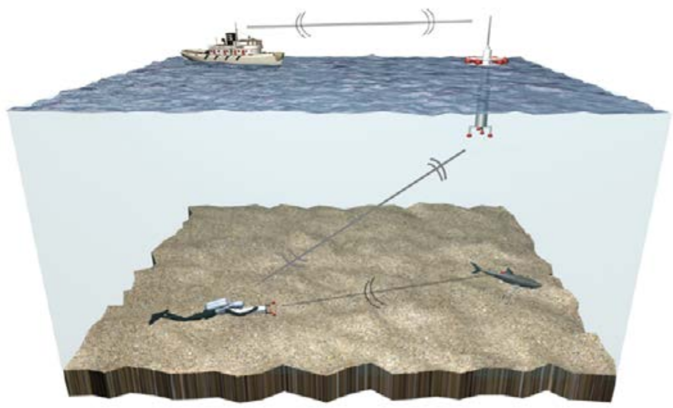


Figure 1: MAST/AM Mission scenario. Source : [6] (Modified).

sition and processing to be compatible with VEMCO© emitters hence being compatible with the most commonly used products.

II. Real Time Architectures For Acoustic Signal Acquisition and Processing

Transmitters used in airborne missions, or on the Earth's surface, use radio-frequency electromagnetic fields to transfer data. However, underwater, a different method must be applied as this radio signals are absorbed by water, and eventually cover short distances. As a result, acoustic signals are preferred for water signaling, as they are able to travel longer distances. The tags employed underwater convert electrical to acoustic energy. A sound wave is basically a pressure wave, and hence detection of an acoustic signal underwater is based on detecting a pressure variation.

Acoustic propagation is naturally slower than radio frequency propagation, which leads to lower communications rates than those of the latter. Furthermore, underwater hight data rate communications using acoustic waves have a greater number of difficulties:

- Travel time spread caused by multipath propagation, via multiple reflections from the surface and bottom or from particles and air bubbles present in the water column.
- Occurrence of Doppler spread of the channel, due to motion from both source and receiver as well as motion of the water column (waves). These motions causes a shift in the frequency of the signal transmitted along each signal path, also known as Doppler shift.
- Increase of frequency directly related with propagation loss.

The latter difficulties depend not just on the location, but as well as in other factors as the weather generated noise and temperature gradients.

1. Acoustic Positioning System Architecture

Acoustic positioning systems can measure range and direction to transponders inserted in underwater vehicles and objects, or derive acoustic ranges from stations deployed onto the seabed, which are held by some form of fixed seabed framework. Acoustic signal acquisition is conducted under the basic principle of capturing and storing intended signals from these sources. The described system is capable of computing the target's position by determining Time-of-Arrival (TOA) of the acoustic signal from the transmitter to a set of receivers with known positions. This can be a set of hydrophones, apart from each other, or an array of hydrophones placed in a non-planar configuration, which allows for 3D target localization.

Based on [9, 1], a basic positioning system (Fig. 2) is based in a reception module which communicates with an seabed transponder. The latter emits with an acoustic signal, which is received on the reception module and processed. The signal is computed through some kind of CPU unit and the result exhibited on some kind of display unit, such as monitor.

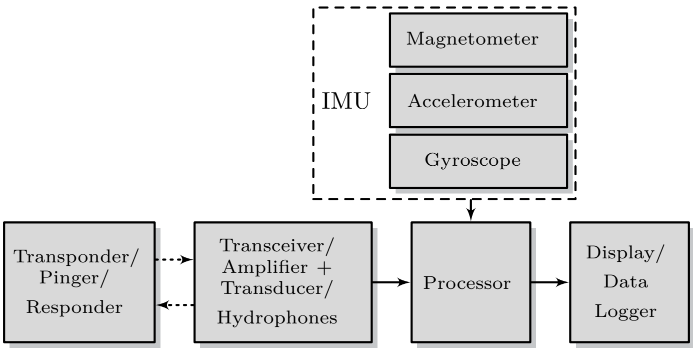


Figure 2: Basic acoustic positioning system architecture.

Some acoustic positioning systems require relative range and direction observations to correct the range and bearing computed. As they are measured relatively to the reception platform's heading unit (usually a gyrocompass), and the reception platform may have suffered some pitch or roll, it must be corrected. For this purpose, some systems embed an IMU.

The module may also possess some kind of interrogator device, for constant communication with an element undersea. For producing an interrogator signal, which will make the undersea beacon respond, the acoustic positioning system can work as a pinger, responder, transponder, or transducer. A transponder requires a interrogator signal to respond to, which results in a continuing communication. In turn, the pinger works periodically. Both responder and transducer require an electric trigger. The transducer does not amplify the week incoming signal, and hence the system must be enhanced with an amplifier.

A comparison between the general architecture introduced for an acoustic position system and the functionalities intended from the MAST/AM project is now relevant. The final product of this project can be designated as a signal reception and processing module whose architecture follows the guidelines of a basic system exhibited herein. Additionally, it was likewise considered a system for signal interrogation, based on an interrogator transducer, which can be added to the architecture if desired.

The most widely used form of getting a signal from a target in tracking missions, in which the MAST/AM project can be included, is to insert a small transmitter in the target's body, which produces a continuous or coded omnidirectional signal, as well as some kind of identification. This tags are available commercially. It is important to stress that it has been due to the decrease of size of transmitters conjugated with an increase of reliability, that it has became possible to perform surveillance missions in smaller species. In this project, the desired signal is collected using hydrophones, which are microphones designed to be used underwater for listening or recording underwater sound. Most hydrophones are based on a piezoelectric transducer that generates electricity when subjected to a pressure change.

2. Ultra Short or Super Short Baseline

The MAST/AM project intends to employ the acoustic position system USBL. In a USBL or SSBL system (Fig. 3) the vehicle has a multi-element receiver array that enables it to measure the angle as well as the range to an acoustic beacon. The system determines the bearing from the vehicle to the beacon by acquiring the signal emitted by the target and by measuring the TOA difference of a single sonar ping between two or more hydrophones. In USBL systems, generally, the distance between hydrophones in the array is of the order of 10cm. USBL is is favored when low system complexity and consumed space constitutes a priority, as it entails the highest noise susceptibility and a more rigorous error handling process.

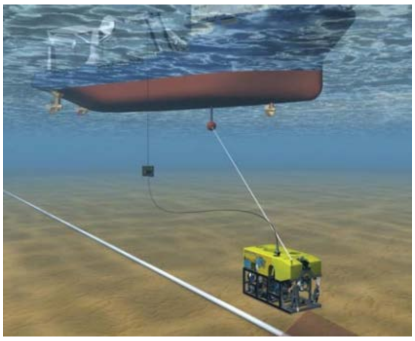


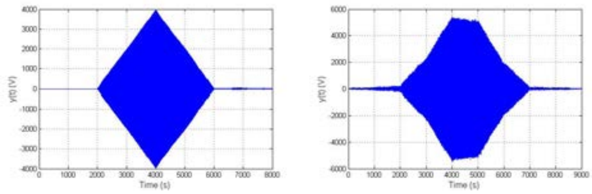
Figure 3: USBL. Source:[1].

3. TOA estimation of a sinusoidal signal

The basic principle of all fine positioning systems is the same: triangulation and/or trilateration based on the TOA of a transmitter signal at three or more receivers. If the receivers are in three dimensions rather than a planar array, there dimensional positioning is feasible. At least three transducers are required, as two only describe a circumference in which the beacon may be, within a degree of certainty. With a third transducer, it is possible to calculate the distance in a third axis.

The most commonly used method for TOA estimation is to put the received signal, starting from a relevant instant of time, through a matched filter. The later maximizes the Signal to Noise Ration (SNR) of the filtered signal, which makes it an optimum method for the detection of signals in noise. The time of arrival is calculated by subtracting the duration of the signal from the time point when the matched filter response reaches its maximum value.

TOA calculation is intended to be used on sinusoidal signals from VEMCO© tags. Unfortunately, this signal type presents difficulties in a successfully calculation of TOA. For prove, attention is called for Figs. 4a and 4b. The former displays the response of the matched filter to a sinusoidal input, with a pulse duration of $T = 2$ms and $f = 250$kHz. The output has a form referred to as a "diamond", with a clearly defined peak. However this form is only achieved in ideal conditions. Fig. 4b shows the response of the matched filter when Gaussian white noise and multipath are present. Multipath was simulated by adding a delayed and attenuated replica to the input of the matched filter. One can see that there is not a clear distinction between the peak in value of the matched filter response to the signal and the peak from the replica signal. Said effect decreases considerable the probability of success for TOA estimation.



(a) Ideal conditions. **(b)** Non Ideal Conditions.

Figure 4: Response of a matched filter to a sinusoidal signal under ideal an non-ideal scenarios.

As mentioned before, the MAST/AM project is to be associated with VEMCO© sinusoidal tags. Looking at off-the-shell underwater emitters available nowadays, to the best knowledge of this thesis' author, small underwater transmitters are only associated with sinusoidal signals. Notwithstanding the difficulties ahead, experiments for the project will still be conducted with sinusoidal signals in order to estimate their reliability. However, as this thesis addresses tracking underwater, it must account for signals more likely to be successful.

4. Real Time Processing and Advanced Signal Techniques

The system performance depends on the accuracy of both the detection of the expected signal and the required processing. The signal may be distorted by additive noise and multipath propagation. In more hazardous acoustic environments, it becomes difficult to distinguish between the direct arrival and multipath interference, so rejection of outliers becomes a key issue. The implemented solution to reduce the possibility of error, is to resort to Spread-Spectrum (SS) methods for signal modulation.

SS is a technique in which the signal is modulated using a sequence of digits (a spreading code or spreading sequence generated by pseudonoise, or pseudo-random number generator), for the purpose of transmitting the signal on a bandwidth considerably larger than the frequency content of the original information [8]. During the transmission of the signal, it hops from frequency to frequency at fixed intervals. At each successive interval, a new carrier frequency is selected. Better SNR and immunity from various kinds of noise and multipath distortion is gained from the last operation.

The use of SS signals requires advanced signal processing techniques only available using real-time digital processing techniques. For the MAST/AM project, a Digital Signal Processor (DSP) was chosen to be center of the acquisition and processing architecture in real-time. This element is a specialized microprocessor with an architecture optimized for the operational needs of digital signal processing. In this project, it performs acoustic signal detection using high-speed FFT. In its usage, the DSP becomes the core of the system, functioning as both system management and data processing. In order to implement an acoustic signal acquisition and processing system, beyond a DSP, it is required a hydrophone set, a signal amplifier and an Analog-to-Digital Converter (ADC). The signal amplifier is used to increase the power of the acoustic signal. Hereafter, the ADC converts the analog signal into digital signal which can then be sent to the digital processor.

III. Complementary Filter

As mentioned throughout this thesis report, the diver is responsible for handling the MAST/AM tool. The handle will be designed as to be closer to the gravity center of the tool as possible, in order to facilitate the tool's maneuverability. However, it is to be expected from the movement induced by the diver to be neither constant or projected on a single axis, which for this case only would be the x axis as the driver is swimming forward. Most likely the diver will unintentionally induce a pitch and roll rotations, generating body frame tilting.

A complementary filter for attitude estimation performs low-pass filtering on a low-frequency attitude estimate, obtained from accelerometer data, and high-pass filtering on a biased high-frequency attitude estimate, obtained by direct integration of gyro output, and fuses these estimates together to obtain an all-pass estimate of attitude. A basic block diagram is given in Fig. 5, for when using this method for pitch estimation.

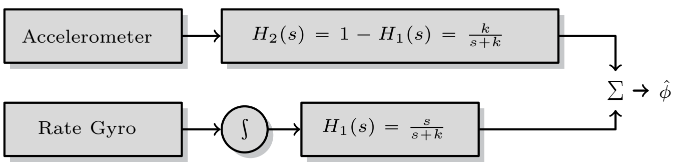


Figure 5: Pitch estimated based on data from IMU using complementary filters.

The movement in Fig. 6 was simulated, illustrating the path of a diver. This simulator was implemented based on the work in [5].

The results obtained for pitch estimation with the complementary filter are very satisfactory. In Fig. 7 we see the direction and depth of the transmitter in $\{B\}$ with and without taking into account the pitch rotation the diver unintentionally induces in the tool. For comparison, the true transmitter's position in $\{B\}$ (considering the simulated vehicle's attitude) is added.

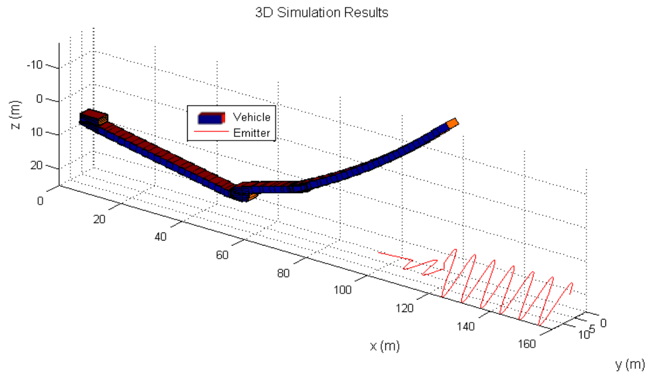


Figure 6: Diver's path simulated.

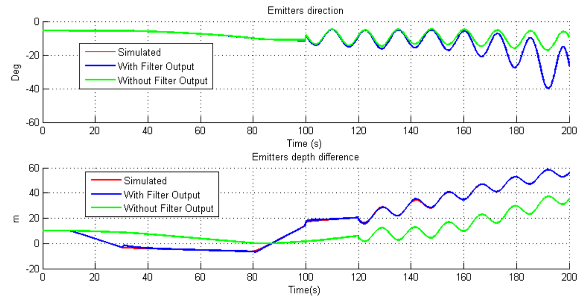


Figure 7: Results of the transmitter's distance and depth difference to the diver when using $\hat{\theta}$.

For direction estimation, it can be stated that complementary filter is only relevant when the transmitter's position in the z axis varies. However, it is quite remarkable the improvement in the calculation of the depth of the transmitter. In this case the complementary filter is highly beneficial.

IV. System Design

The proposed hardware and software architecture consists on an USBL array combined with an interrogator transducer and electronics responsible for signal acquisition and processing. The interrogator transducer is used when communication with a vessel at the surface is necessary. As a side note, there is no need for a propulsion or a depth control system, as the tool's movement is induced by the diver.

1. Acoustic

1..1 Hydrophone

The set of hydrophones selected were from HIGH TECH©, model name: HTI-96-MIN . They have a frequency response from 2Hz to 30kHz and can operate up to 500m depth with no signal degradation. Connection of the hydrophone array to the tool was implemented through an Impulse IE55 Connectors. This connector is used for power transmission and signal telemetry.

1..2 Transducer

The interrogator transducer employed is the Model ITC-1042 (Fig. 8b) . This is a spherical transducer which offers broadband omnidirectional transmitting and receiving response with efficiencies of over 50%.

1..3 Underwater Acoustic Tags

It was selected the VEMCO© $V16$ Continuous Transmitter model, with 16mm of diameter and 68mm in length, and a data frequency of 63kHz. For this model, VEMCO predicts a life-time of approximately 200 days.

2. Hardware Architecture

2..1 Array

An USBL is used in the MAST/AM project as the acoustic positioning system. The USBL array was built using Bosch-Rexroth© aluminum rods and connections (Fig. 8c), which allows for a highly configurable array structure, for optimal design during the evaluation and testing phases.

(a) Hydrophone **(b)** Transducer. **(c)** USBL array.

Figure 8: Acoustic devices plus USBL array.

2..2 Signal Processing

Inside the watertight tool, a DSP acquired analog data samples through an ADC available on the a D.SignT.Module.ADDA16, and generating an interrogator signal using Pulse-Width-Modulation (PWM). The DSP should have sufficient processing power to operate in real-time. The tool uses a D.SignT.Module.C6713 a high performance floating point DSP board. Furthermore, the DSP has an Ethernet interface, thanks to a D.SignT.Module.91C111, which is used as an outbound communication link for data analysis. The use of a DSP eliminates the need of an external CPU. Also it is considerable smaller than any small PC available in the market, which is beneficial for the project considering the intended small dimensions of the tool.

Each hydrophone signal is routed through an Automatic Gain Control (AGC) signal amplifier board developed at ISR/IST, whose gain can either be let in automatic mode or overridden by an analogue voltage control from the DAC available on the DSP module. The DSP receives the data and stores it in memory without interrupting the core processor which is doing time-critical acoustic signal processing (Fig. 9). Additionally, if so is desired for the navigation filter, at specified instants of time, the DSP will send out a ping to the transponder, which in turn communicates with a vessel at surface.

Figure 9: Architecture for signal acquisition and processing.

The hydrophones are connected to the AGCAMP stack, which in turn are connected to the D.Module.ADDA16's D/A converters. These converters send data to the DSP stack through DMA. A brief definition of this controller is hence called for. DMA enables data transfer without interrupting the CPU. The CPU has only to configure the DMA, but is then free to other processing even when DMA is transferring data. One must only be careful in such occasions when the CPU and the DMA are accessing the same memory position. In the MAST/AM project, the CPU will only access data once the DMA has finished storing it in memory.

3. Interrogator System

An interrogator is added to the architecture (Fig. 10) for the purpose of communicating with an USBL system on the surface, required when the implemented navigation algorithm calls for additional information concerning the diver's location. The PWM signal to the interrogator transducer passes through a Class D power Amplifier (PWRAMPD) board developed at ISR/IST.

Figure 10: Interrogator system architecture.

3..1 Visualization Hardware

As part of the MAST/AM project, the diver handling the tool underwater must have some kind of visualization interface indicating which direction they must follow to further reach the target. At an initial phase of the project, it was decided to use an Android device as a visualization platform. Combining a high performance with a slim design, the Android device fully meets the requirements of this project. The selected device was a Samsung© Galaxy SIII LTE, Android OS, V.4.1.2 (Jelly Bean). It is noteworthy that this device will render visualization of the computed data solely, hence it does not require real time processing like the DSP.

As mentioned before, a DSP is responsible for the data processing in real-time. After processing, the DSP must send the results to the Android device to be displayed to the diver, for which they must be connected. The Android device is connected the Ethernet output interface of the D.SignT.Module.91C111 through an USB/Ethernet adapter.

4. Inertial Navigation Systems

A Microstrain 3DM-DX3©-35 will be IMU of the portable underwater tool, which is connected to the DSP's RS-232 serial link, with a baud rate of 115200bps. The DMA stores the data from the Microstrain. Hence it does not interrupt the real time acquisition and processing of the acoustic signal from the hydrophones. The DSP processes this stored data when it is most convenient.

4..1 Outbound connection

An outbound connection was added to the architecture of the tool for the purpose of analyzing the system's performance. An Ethernet connector was used in the tool for outbound communications. In the end of the tool (opposed to the end with the hydrophones), an Ethernet interface was included, thus allowing a PC to receive data from the signal processing architecture. For the purpose of constructing a "three intervening" connection, between the DSP's Ethernet interface, the outbound connection and the Android device through the Ethernet/USB adapter, an Ethernet switch was added to the architecture (Fig. 11).

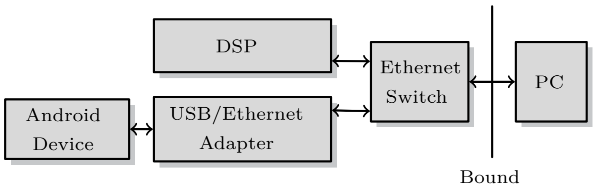


Figure 11: Outbound Connection, DSP and Android's device connected through an Ethernet switch.

4..2 Temperature and Pressure Reading

For temperature and pressure reading inside the MAST/AM tool a Bosch Barometric Pressure Sensor (BMP) 085 was employed. A microcontroller board AVRCAN128 developed at ISR, is interfaced with the BMP sensor. This microcontroller acts as the "brain" that controls the sensor. The AVRCAN128 board is connected to a Sparkfun©'s XBee Explorer USB , which enables communication with an USB device. The Android Device acts as an USB device, which makes it possible for it to be attached to the XBee Explorer. Taking into consideration the fact that the Android device is also intended to be USB/Ethernet adapter, a small USB was added to the architecture to couple both devices to the Android device (Fig. 12).

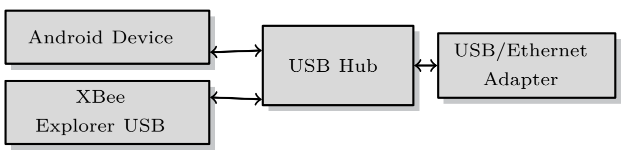


Figure 12: Connections established with the Android device.

Inside the tool, pressure grows as a result of the temperature rise. The tool requires low pressure to enable sealing O-Rings in the tool's lid and to maintain the tool watertight. The O-Rings are used for the two static seals on the tool, as they provide a simple and reliable method. In addition, they require very little-structure and mechanics to implement.

A style of male piston was used in the implementation of the O-Rings. In this sealing method the O-Ring is placed in a gland on the male part, which is inserted into the female part. The O-Ring seals against the inner diameter of the female part and the outer diameter of the male part. According to [2], the use of a piston seal is favorable since the O-Ring stays in place better during installation due to being stretched over the male part.

For analysis purpose, a feature was implemented in the Android device which acts as recorder for the data outputted from the Sparkfun© BMP085 sensor. Fig. 13 shows the result of an experiment where the tool was sealed and all the electronics powered. The tool was connected to a constant power source which enabled the experience to be conducted for an amount of about 5.15 hours in order for a point of thermal equilibrium to be observed. At the closing of the tool, pressure is set at a value of 0.5bar, by resorting to an air pump connected to the tool's pressure port (Fig. 14). The pressure port is sealed with a pressure port screw, which has a small O-Ring to ensure proper seal of the port. Both a warning sound and a visual sign generated by the Android device will go off.

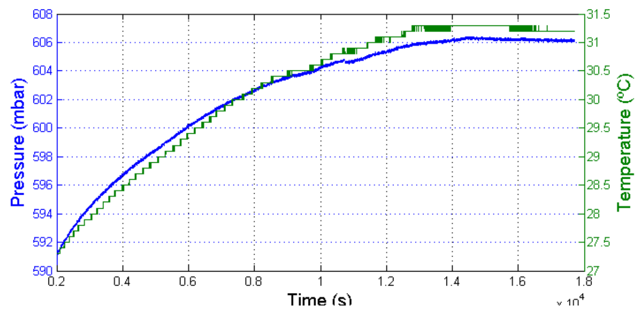


Figure 13: Evolution of pressure and temperature values inside the MAST/AM tool.

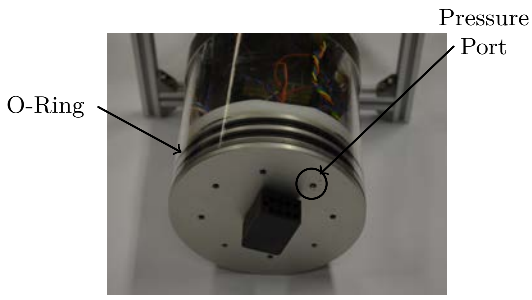


Figure 14: O-rings at one end of the MAST/AM tool.

Throughout the mission, it will be considered a threshold of safety equal to 0.65bar. From the moment at which the pressure value exceeds this value, both a warning sound and a visual sign generated by the Android device will go off.

4..3 Power Source

For batteries, it was chosen to use a 230Wh Lithium-Polymer rechargeable battery pack, assembled from four Kokam© High Energy Density Cells, of 16Ah each, with a nominal pack voltage equal to 14.8V. The batteries are located at the inferior half of the tool, in order to lower the center of gravity. A Battery Monitor (BATMONIT) board, developed at ISR, is used in order to control a

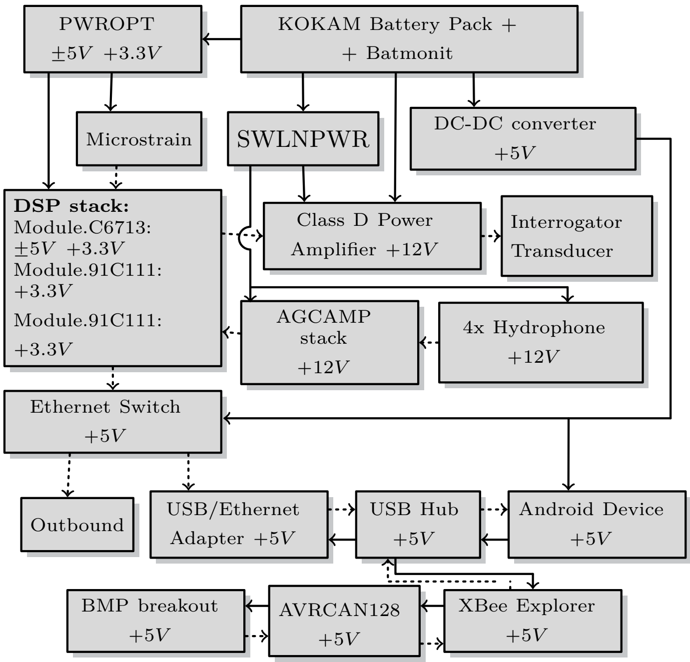


Figure 15: Architecture of the prototype for the MAST/AM tool. —— power, −− data

switch which allows to transition between states on, off, and charging state. Furthermore, it monitors charge and discharge voltage and current. To be noted that the available time for each dive depends on the batteries' life time. The battery pack powers the entire system. All electronics, except for the Android device, are powered up when the battery pack is switched on.

The electronics are not powered directly by the battery pack as their voltage value is not constant, as their values tend to decrease. There must be a power conversing between battery pack and electronics in order to guarantee a constant voltage value, and also to provide galvanic isolation between battery packs and electronics. Three boards were used as power conversing. Two developed at ISR: a Power Supply/Can opto-isolation and termination/RS-485 board (PWROPT0485) and a Switching Low Noise Power (SWLNPWR), plus a DC-DC converter board with a TRACO POWER© TEN 15-2411 which outputs +5V. The division of power from the battery pack to all three boards is made by a Power Distributor Board (PWRCONN).

The PWROPT0485 board has two high performance DC-DC converter modules: TRACO POWER© TEN 10-1221 and TEN 15-2410, which output a voltage of $\pm 5V$ and $3.3V$. The SWLNPWR board will generate a regulated voltage of $12V$. PWRCONN is again used for power splitting at the output of both boards.

A complete block diagram of the prototype architecture with power supply information is displayed in Fig. 15.

4..4 System Autonomy

Determining system autonomy is vital for determining the dive total duration, as the life-time of the battery pack has direct influence in the time the electronic devices are operational and consequently the time the diver is able to visualize data concerning the target's position.

A power budget analysis will be used to determine how long the MAST/AM tool will operate without recharging. This estimation was made under the assumption of the largest consumption, that is, under the worst efficiency. Therefore, it is expected that this estimation differs for the worst from the results obtained in experiments in real scenario.

During this analysis, certain elements were not included, as they consume negligible currents, in the order of few mA. These elements are the BATMONIT, and SWLNPWR boards. The PWRAMPD power consumption depends on the periodicity of which the interrogator transducer produces signal. The periodicity was not study during the work of this thesis as it will depend of the requirement of the navigation filter implemented in the MAST/AM tool. Consequently, the PWRAMP will not be added to the system autonomy analysis. However as this analysis will be based on the largest consumption and the PWARAMPD has low consumption, the lack of this device does not affect significantly this estimation. The result of the latter analysis can be found in Tables 1 and 2. For Table 2 the values correspond to the maximum power consumption available in the devices' specifications. For table 1 the assumptions made for finding the power consumption are presented below.

	PWROPT		DC-DC	AGCAMP stack
	TEN10-1221	TEN15-2410	TEN15-2411	
V_{CC}	$+14.8V$		$+14.8V$	$+12V$
W	0.96W	7.66W	1.49W	0.14 W

Table 1: Consumption of devices inside the MAST/AM tool found by assumption.

	DSP stack			Micro- - strain	Android + Connecting Devices	Ethernet switch
V_{CC}	$+5V$	$-5V$	$+3.3V$	$3.3V$	$+3.3V$	$+5V$
I	$0.08A$	$0.07A$	$2.01A$	$0.25A$	$1A$	$0.5A$
W	0.40W	0.35W	6.633W	0.825W	3.3W	0.25W

Table 2: Consumption of devices inside the MAST/AM tool found experimentally.

A brief note regarding Table 2: the value of $2.06A$ may seems exaggerated but it is necessary to recall that this corresponds to the max power consumption of the DSP boards: $1.5A$ from the D.SignT.Module.C6713, $0.4A$ from the D.SignT.Module.ADDA16 and $0.16A$ from the D.SignT.Module.91C111. Both the PWROPT and the DC-DC were developed around TRACO POWER cells. According to their specification, the TEN 15-2410, TEN 15-2411, TEN 10-1221 have a efficiency equal to 80%, 84% and 78%, respectively. Assuming these values, this cells have a power consumption of:

$$W_{TEN10-1221} = \frac{0.4\text{W} + 0.35\text{W}}{0.78} = 0.96\text{W}$$
$$W_{TEN15-2410} = \frac{6.633\text{W} + 0.825\text{W}}{0.8} = 7.66\text{W} \quad (1)$$
$$W_{TEN15-2411} = \frac{1\text{W} + 0.25\text{W}}{0.84} = 1.49\text{W}.$$

Each AGCAMP has a Quiescent Supply Current of $2mA$. With a supply voltage of $12V$, gives $W = 0.096W$ for the AGCAMP stack. By considering that the DC/DC which powers this device has a performance of 70%:

$$W_{AGCAMP} = \frac{0.096\text{W}}{0.7} = 0.14\text{W}. \quad (2)$$

By adding the values of power consumption previously presented, the MAST/AM tool has a total power consumption of 24.414W.

According to the battery pack specifications, it has a capacity, C, value equal to $16Ah$ and a nominal package voltage of $14.8V$, which results in a energy of 230.4Wh. In practice, a Lithium-Polymer battery cannot be repeatedly 100% discharged. Therefore, it is necessary to de-rate the battery by some amount. Considering that a maximum of 60% of the battery power will be used continuously, results in a energy of 138.4Wh. Consequently, the practical time between recharge is approximately:

$$T = \frac{138.4\text{Wh}}{24.414\text{W}} \approx 5.67\text{h}. \quad (3)$$

The power consumption was tested by connecting the MAST/AM tool to a constant power source of $14.8V$ through the Subconn©. It was observed that the tool consumed a power equal to $19.24W$. As expected this is below the maximum power consumption estimation. Hence is guaranteed the estimation of a time between recharge differs for the worst from the results obtained in experiments in real scenario. A time duration of 5.67 hours for a continuous operation is considered to be a very satisfactory value.

4..5 Dimensions and Weight

Prior to its implementation, the design of the *MAST/AM* tool, and the electronic devices inside, were designed using the SOLIDWORKS© software. Hence, it was possible to automatically conjugate the decision of adding a device to the tool's interior with the validation that said device was liable to be installed. The designed disposition of all electronic devices inside the tool can be seen in Fig. 16.

The dimensions of the MAST/AM tool are presented in Fig. 17. For handling by the diver, a system with two vertical bars is assembled to the tool, each to one side of the tool, which the diver will use in order to maneuver the tool. The final prototype is displayed in Fig. 18. Upon the implementation of the prototype it was seen that the tool weighted approximately 6 kg.

4..6 Connectors

During the description of the implemented design for the portable underwater tool, three forms of data communication from an outside source to the inside of the tool were reported: the signal received from the hydrophone array, signal sent to the transducer and the outbound Ethernet connection through the Ethernet switch. Such connections were only possible by resorting to connectors specially designed for underwater applications, able to withstand the hazardous conditions the underwater environment can produce.

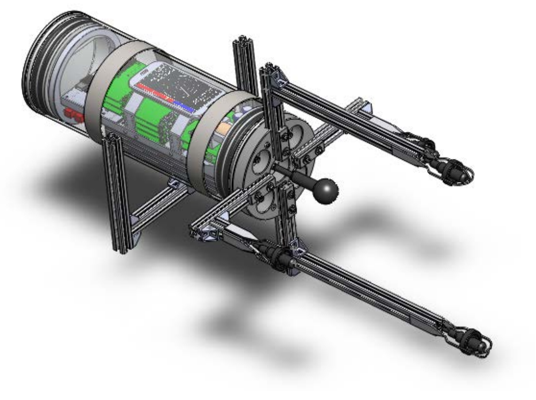


Figure 16: Final prototype of the MAST/AM tool made in SOLIDWORKS©.

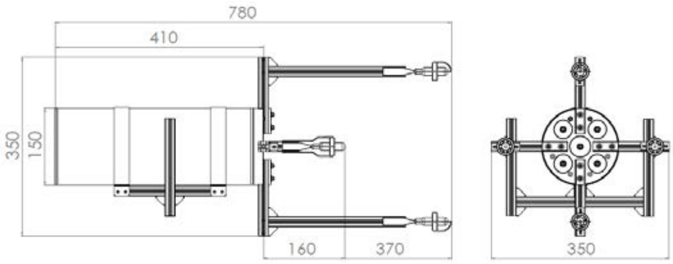


Figure 17: MAST/AM tool dimensions (mm).

Figure 18: MAST/AM portable underwater tool.

Connection of the hydrophone array and transducer to the tool was implemented through an Impulse IE55 Connectors. This connector is used for power transmission and signal telemetry. Body and engaging nut are 316 Stainless Steel. The female of this connector is inserted at one end of the tool's (Fig. 19a).

The Ethernet connection is made possible through a SubConn© 9 Contacts connector. This connector enables an Ethernet connection, a Pulse Per Second (PPS) connection and power transmission, which may be used as power source for the tool. The female connector for the Subconn© is inserted in the opposite side of the hydrophone array (Fig. 19b).

(a) Hydrophones connected through the IE55 connector. **(b)** SubConn© female connector.

Figure 19: MAST/AM tool connectors.

5. Software

As part of the MAST/AM project, the diver handling the tool underwater must have some kind of visualization interface indicating which direction they must follow to further reach the target. It was decided to use an Android device as a visualization platform. Combining a high performance with a slim design, the Android device fully meets the requirements of this project. It is noteworthy that this device will render visualization of the computed data solely, hence it does not require real time processing like the DSP. The Android device will be connected to the DSP stack Ethernet output interface of the D.SignT.Module.91C111.

The main goal of the design phase was to create an *user-oriented* interface which could be correctly interpreted without the need of previous training. Additionally, the interface employs colors with a clear contrast between them, so the displayed information could somewhat be interpreted with peripheral vision.

The screenshot of said application can be seen in Fig. 20. In the left side of the screen, the diver can visualize an object very similar to a compass which will point the direction of the transmitter in the same plane as the diver. The distance in the previous plane is also visible through red circumferences. The farther the diver is from the transmitter, the larger is the radius of the red circumference, and vice versa. In the right side, a vertical bar displays the distance between the diver's and the transmitter's depth. If both are at the same depth, the percentage of blue and red in the bar will be equal. If the diver is at a higher depth, the percentage of red will be bigger, denotative that the diver must lower its depth. As the diver decreases its depth, the red bar decreases in size, meaning the diver's depth is getting closer to the transmitter's depth. If the diver is at a lower depth, the red bar will be smaller than the blue bar, meaning the diver must increase its depth. In the bottom of the screen, is also visible a written information concerning the angle, distance and depth difference towards the transmitter.

V. System Validation and Assessment

The first experiment with the MAST/AM tool at sea was conducted at Albufeira Dock, Portugal, July 19^{st}. The experiment results showed a successfully acquisition of the signal, including at a distance to the transmitter of over 220m. However, unfortunately, the outcome of said estimation showed both a large variation from correct values and randomness throughout the entire experiment duration. Theoretical analysis upon sinusoidal signals, confirmed that for direction results with a reasonable degree of certainty to be obtained, a higher SNR was required. Efforts were redirected at experimenting with different signals with greater evidence of success, namely resorting to SS methods.

The second experiment was conducted at Belém Bay, Portugal, October 4^{th}. A signal producing system was connected to a transducer for generating the transmitter signal. The signal was based on the SS method. Fig. 21 display the various locations where the transducer was positioned with respect to the hydrophone array at the origin of the arrows. Each location will be designated by the number adjoining the arrow targeted to said location. It is admitted that all positions are at the same altitude. The distances between positions were calculated according to their GPS positions. The signals produced by the transducer, at each location, were analyzed. Different directions of the USBL array were considered for each experiment. The reader must take into consideration that the placement of the array in a given direction was carried out manually. Hence when we expect, for example, a 0° by positioning the array directed to the transducer, this is a 0° read by the human eye. In reality, this may easily be an angle of a small value, but not null.

Table 3 presents the outcome of the direction and distance calculation when the transducer was at the position indicated in the first row. The values presented are the output of a median filtering of the raw signals in order to lessen the effect of outliers.

The results are very satisfactory considering the high possibility for measuring errors in such location. Firstly, the depth is diminutive which results in a continual multipath caused by reflections from both the water surface

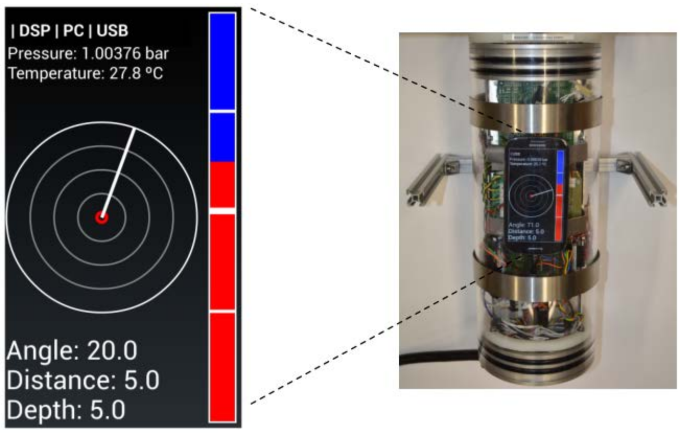


Figure 20: Diver graphical user interface.

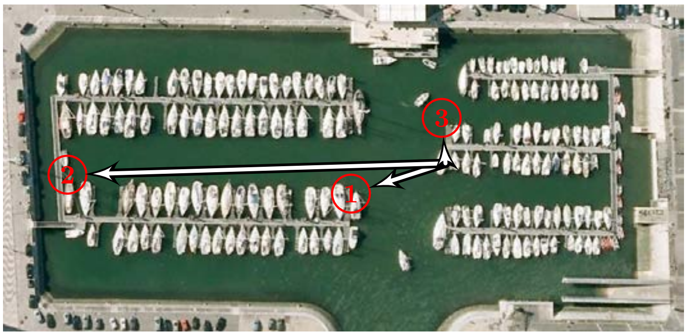


Figure 21: Belém dock sea trials setup.

Transducer Position	1		2		3	
	Mean	σ	Mean	σ	Mean	σ
USBL Heading **(expected)** (°)	8.15 (**0**)	3.67	2.46 (**0**)	1.59	23.29 (**90**)	9.09
Distance **(expected)** (m)	39.9 (**38**)	2.23	135.85 (**132**)	2.86	11.04 (**12**)	1.44

Table 3: Results from experiment at Belém Dock.

and ground. Secondly, the existence of several vessels also gives rise to additional reflection. It should also be taken into account that the placement of the array in a desired direction for testing was carried out manually, and hence a random deviation from the direction intended must be accounted for. Additionally, an irregular deviation is accredited due to the undulation of the water column (waves), which displaced both the hydrophone array and the transducer. It is also worthy of mention that the poor quality of position 3 comparatively to position 1, regardless of its closer proximity, is due to to reflections induced by a vessel stationed between position 2 and the hydrophone array at the time of the experiment. Lastly, it must be noted that for the propagation velocity of sound in water an overall value was used. It can be expected that this value differs from the one at the test site, affecting the certainty of the results.

Overall, regarding the implementation of the designed prototype, experiments often conducted in laboratory of the complete system and of the signal acquisition system tested in real environment were successful. The objectives initially set for the portable underwater tool were accomplished as the tool intended performance was implemented successfully. Unfortunately, initial guidelines for the MAST/AM project were not met in full, as with VEMCO© tags results obtain were far less satisfactory. The initial intention of designing a prototype was attained with the slight misfortune of requiring transmitters dissimilar of the ones assembled by the VEMCO© brand.

VI. Conclusion and Future Work

It was proven that the prototype is capable of acoustic signal acquisition, being assembled with an acoustic array, and processing provided by a DSP. The computed results are delivered to an Android device which will display the data to the diver, along with pressure and temperature values inside the tool. The tool is also equipped with an underwater acoustic interrogator unit, required for certain navigation filters for communication with a vessel at surface. The final architecture prototype was successfully validated with experimental data obtained at sea. It proved to be fully functional, low cost and and low power enabling continuous operation of approximately 5.6 hours.

Concerning future work, efforts would certainly be directed towards the development of practical and small dimensions emitters with different signal properties that the ones observed in VEMCO© transmitters, or even development of processing and signal acquisition techniques which would eventually allow the use of the existent VEMCO© tags. It is also of importance to bear in mind that the project was conducted under academic purposes, it is still at a prototype phase, and all individual components were assembled together. If it were to be applied to a more commercial environmental, fabrication of components specific for this tool would certainly avail to diminish both size and weight of the tool further increasing its potential use.

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