AUV Control and Communication using Underwater Acoustic Networks

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***Abstract*— Underwater acoustic networks can be quite effective to establish communication links between autonomous underwater vehicles (AUVs) and other vehicles or control units, enabling complex vehicle applications and control scenarios. A communications and control framework to support the use of underwater acoustic networks and sample application scenarios are described for single and multi-AUV operation.**

Index Terms— Underwater acoustic communication, Marine vehicles, Mobile Robots

I. Introduction

THIS paper describes the use of underwater acoustic networks for autonomous underwater vehicle (AUV) control and communication. This work was done in the context of the PISCIS project [1], undertaken by the Underwater Systems and Technology Laboratory (USTL) from University of Porto and demonstrated in a cooperative mission with vehicles and technologies developed at the Center for AUV Research, Naval Postgraduate School, CA/USA.

The PISCIS project has developed a system for the mixed initiative control and coordination of multiple autonomous underwater and surface vehicles for oceanographic and environmental data collection in a networked environment. The system consists of 1) AUVs and ASVs (autonomous surface vehicles) equipped with acoustic modems for underwater communications, radio/GPS systems for interactions at the surface, 2) buoys equipped with transponders for acoustic localization, 3) a sensor network and 4) human-operated command and control units (CCU). This dynamic environment provides services for vehicle tele-operation, tele-programming and supervision, data collection from a sensor network, and system supervision and aggregation of information collected in real-time.

The Center for AUV Research at the Naval Postgraduate School was established in 1987 to educate future Navy leaders in the development and application of AUV technology. In support of this mission, the Center performs cutting-edge research and develops innovative concepts with potential for advancing naval AUV operations. One such concept for enabling cooperative, multi-AUV operations uses a network server vehicle [2] to download data from other vehicles performing survey missions and convey this data to human operators. This concept is most effective when the server vehicle can rendezvous with survey vehicles still underway, as close proximity allows for high-speed acoustic or optical data communications and survey vehicles do not have to interrupt their missions to offload data.

Considering these work objectives, where networked operation of AUVs with complex requirements is involved, there is a great interest in deploying underwater acoustic networks, that can be quite effective to establish communication links between AUVs and other vehicles or control units. This paper provides a description of a communications and control framework for that technology and of their application in AUV operation, as follows. Sections II and III describe the developed communications and control frameworks. Section IV describes AUV operational scenarios for these frameworks. Section V concludes and highlights future items of work.

II. COMMUNICATIONS FRAMEWORK

A. Hardware

Teledyne Benthos ATM-855 modems and AT-12ET LF (Low Frequency 9-14 KHz) transducers [3], shown in Fig. 1, were used for deployment on AUVs and connection with control consoles. Using this hardware setup, transmission speeds of up to 1200 bps is possible. The core functionalities provided by the acoustic modems include the actual messaging capability and range estimate facility, plus associated configurations, accessible through the modem's firmware AT command set.

To enable longer range operations and simplified access, the use of acoustic modems can be combined with spread-spectrum radio frequency modems that are used as gateways

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to the actual acoustic modems. The RF modem gateways can either be deployed on static locations or moving gateway/server vehicles [4], enabling long range and high-rate access to acoustic modems. This technique has the obvious benefit of multiplexing access to acoustic modems over long distances by several network nodes, with much less expensive hardware compared to underwater acoustic communications equipment. The particular RF modems we use, shown on Fig. 1, are from MaxStream [5], operate at 900 MHz or 2.4 GHz, providing up to 11.3 km (7 miles) operation range and a throughput rate of 19200 bps.

B. Software interface

To address the use of acoustic modems a simple and modular software interface has been developed and integrated in the development of the Seaware middleware for multi-vehicle networked systems [6] developed at USTL. Fig. 2 and Fig. 3 summarize the software infrastructure that can be deployed for AUVs or other marine vehicles (e.g. ASVs) and control consoles using different operating systems (Linux, Windows, QNX) and programming languages (C/C++, Java).

Seaware provides a publish-subscribe interface for applications to exchange data in a network through a set of transports, including Wi-Fi and RF modem (which can be used not solely as a gateway to acoustic modem) enabled networking. In regard to underwater acoustic networks, the Seaware software interface has three basic modular layers, described as follows:

1) Low level modem access: the low level software interface is the modem's AT command set, understood by the modem's firmware and accessible through a RS-232 serial connection or a RF modem gateway (to the actual RS-232 port).

2) Modem access library: a modem access API encapsulates low-level “AT programming” and serial configuration and provides the kernel operations to operate an acoustic modem: setting the modem just by passing parameter values, sending and receiving messages and issuing range requests. Thus modem configuration and operation is not “manual” and low-level, instead it is structured around an API which abstracts modem access. As it is, the modem access library can be used on its own to provide a messaging interface to acoustic modems.

At this level, since underwater communications can be significantly slow, noisy and unreliable, each message sent through the acoustic modem is encapsulated in a compact packet, defined by a 1-byte header, containing routing and compression information (the 7-bit encoded sender modem address, plus a bit flag indicating if the message payload is compressed - on-the-fly data compression can be used on request), followed by the actual message payload and ends with a two-byte CRC tail.

3) Publish/Subscribe API: the intermediate messaging API is finally hidden through the Seaware publish-subscribe API in which peers communicate based on publication and subscription of *topics*, abstracting away details of the underlying transport mechanisms.

Fig. 1. Hardware: Benthos Acoustic modem (left) and transducer (middle) [3] (left) and MaxStream RF modem] (right).

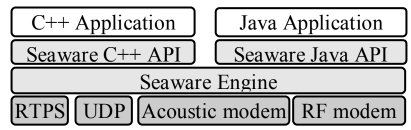

Fig. 2. Seaware software architecture.

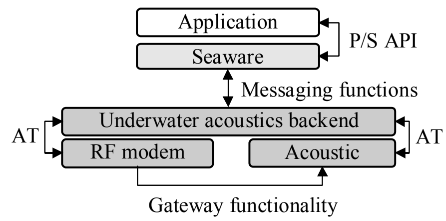

Fig. 3. Seaware support for underwater acoustic communications.

The software interface described here provides a simple and modular form of handling acoustic communications, albeit with some limitations, if compared to more state-of-the art work in the field [7]-[8]. For example, it does not provide built-in support for time-division multiple-access (TDMA) messaging, meaning interference in the half-duplex underwater medium depends solely on application logic; it does not also provide built-in *store-and-forward* mechanism to cope with message loss and intermittency in communications. The raw message reliability scheme provided is based in the Benthos' modems simple per message acknowledgment-retransmission mechanism. That said, it is conceivable to extend the software interface described here to handle these more advanced requirements (and so is our objective). Also, as it is, the software framework capabilities prove to be powerful enough even for less trivial applications in AUV communication and control, as described in section IV.

III. CONTROL FRAMEWORK

A. AUV control messages

A control language defined by a simple and compact message set is used for AUV control, as summarized in Table 1. The message set is logically split into AUV requests and acknowledgments. Apart from the payload induced by the communications layer (1 byte header, 2 byte footer), each message has a 1 byte tag that identifies the message type, which is optionally followed by data values. The message set's compact definition has the aim of reducing transmission time and errors.

The following core types of messages are defined:

1) *Mission control commands:* can be used to tell the vehicle to either start or abort mission execution. Upon reception of the mission start command, the vehicle's internal software enables execution of a pre-loaded mission plan. An executing mission can be aborted later with the mission abort command. Upon mission termination, the vehicle sends an asynchronous status message.

2) *Vehicle status commands*: can be used to get an estimate of vehicle's navigation status (estimated position, velocity and current mission objective) and current internal status (for example regarding internal temperature or remaining battery power).

3) *Rendezvous mode switching commands*: these are specific commands related to rendezvous operation for joint operation with the NPS rendezvous message protocol described in section IV. The rendezvous mode switch commands simply toggle the rendezvous operation mode on or off.

The described message set is part of the more broad Inter Module Communication (IMC) API [9] developed at USTL, that defines a general control language for interactions with autonomous vehicles in the form of a message set. The IMC API abstracts differences between different types of vehicles (AUVs, UAVs[1], ASVs and ROVs[2]) in most of its definition, albeit specific messages per vehicle type or communication medium are also defined (as in the described case). The use of control languages for autonomous vehicle operations is a standardized approach for communication and control, in which all parties respect the control language format and protocol. Good examples of similar work can be found in [10]--[12].

B. Neptus Command & Control Unit (CCU)

The Neptus CCU [13]-[14] is used to plan, execute and monitor autonomous vehicles missions, real-time data dissemination and post-mission data review. For this Neptus provides several modules: the Mission Planner to plan the mission; the Mission Console(s) to monitor and command the vehicles; the Mission Review & Analysis to plot the data and replay the mission execution; and disseminate the mission data in real-time to the web.

The Neptus Mission Planner module (Fig. 4) is used to create the virtual representation of the operational scenario and the AUV mission path. The mission is treated as a set of maneuvers and transition conditions between the existing maneuvers. Currently only the 'true' condition is supported by the AUVs we operate, being only possible to define sequential missions, where each maneuver is executed whenever the preceding maneuver has ended successfully.

From the user point of view, the mission can be treated as a geo-referenced path where each waypoint represents a maneuver to be executed and its specific parameters. Neptus allows these waypoints to be defined by clicking on the map or dragged in the same way.

[1] Unmanned Air Vehicle
[2] Remotely Operated Vehicle

TABLE I
AUV CONTROL MESSAGES

Command	Request & Reply Tags	Request & Reply Payloads (bytes)[1]	Description
Start Mission	0/128	4 / 4	AUV start mission request.
Stop Mission	1/129	4 / 4	Causes AUV to abort current mission being executed.
Mission State	2/130	4 / 19	Get AUV mission state (completion status, position, velocity, leg number).
Vehicle State	3/131	4 / 7	CCU request for an update on the AUV's internal state.
Rendezvous on	4/132	4 / 4	Toggles rendezvous mode on.
Rendezvous off	5/133	4 / 4	Toggles rendezvous mode off.
Invalid CRC (reply only)	255	4	A peer acknowledges message receipt but with error due to CRC checksum mismatch.

[1] Includes 1 byte-header and 2-byte CRC footer.

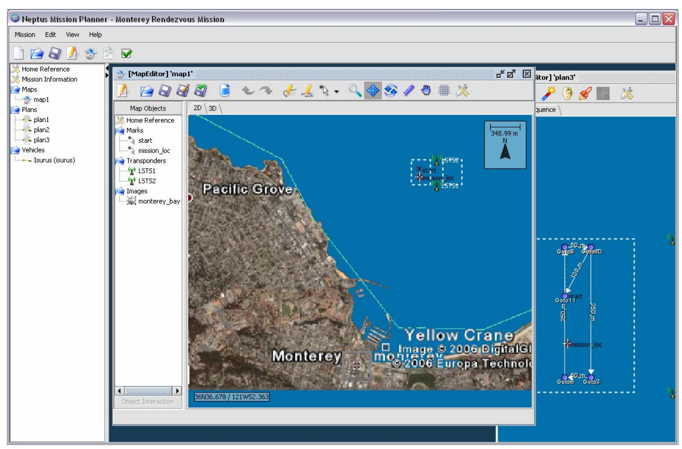

Fig. 4. Using the Neptus Mission Planner module to define AUV missions.

Environmental maps are created by defining the mission central coordinates and by connecting to a remote Web Mapping Service (WMS). In addition, other objects like polygons, images, path drawings and generic 3D models can also be added using the same module.

The mission definitions can be stored on disk as XML (eXtensible Markup Language) files, including maps, associated vehicles and plan specifications. This allows the mission translation to different vehicle native formats recurring only to a specific XSLT (eXtensible Stylesheet Language Transformations) style sheet. We have used this feature thoroughly in real missions, when having different vehicles operating simultaneously in the same area. Using Neptus it is possible to define a single mission file that is converted to the various vehicle formats. This has been done in the Monterey bay tests with NPS (see Section IV).

Neptus provides various operating consoles; each one adapted to a specific vehicle or mission execution needs. There is also the possibility for user defined consoles, dragging visual components to the console interface and connecting these components to environment variables.

A specialized console (Fig. 6) was created to monitor the Isurus vehicle and control the overall execution of previously defined plans.

After execution, the mission log file can be replayed using the same console or can be revised using the Neptus Mission Review & Analysis (MRA) application [15].

IV. SAMPLE APPLICATION SCENARIOS

A. AUVs

The described communications and control frameworks have been tested in single and joint AUV operations, conducted at Monterey Bay/CA, USA and at the Leixões Harbour, Portugal. The Isurus and Aries AUVs shown in Fig. 5 were used for this purpose.

Isurus is a REMUS (Remote Environment Measuring UnitS) class AUV [16], built by the Woods Hole Oceanographic Institution, with several hardware and software subsystems improved or specifically developed later [1][17]. The vehicle is equipped with a Wi-Fi interface for surface communications, an acoustic modem for underwater communications and provides a physical platform for oceanographic surveys, using a wide range of sensors such as CTD, altimeter, side scan sonar, ADCP, optical back-scatter, etc. Autonomous navigation is done using acoustic LBL fused with dead reckoning by a Kalman filter.

The ARIES (Acoustic Radio Interactive Exploratory Server) AUV [2] was designed and built at NPS. Six lead-acid batteries power two stern-mounted electric thrusters. Pairs of dive planes and dorsal rudders mounted at the bow and stern provide pitch and heading control. Navigation sensors include a ring laser gyro-based inertial measurement unit, Doppler velocity log, magnetic compass, and GPS receiver for periodic navigation corrections on the surface. Designed as a network server vehicle, ARIES carries radio and acoustic modems for inter-vehicle communications and can function as a node on a wireless network.

B. Single AUV operations

The single AUV control scenario involved the Isurus AUV and the core control commands presented in Table 1. Tests were conducted at the Leixões harbor in Porto and at Monterey Bay. Using the control and communication framework described in the previous sections, it was possible to control the AUV mission's execution and obtain real-time monitoring data for the vehicle state through a control console (Fig. 6).

Isurus' state is monitored using one of the three available communication means: Wi-Fi, acoustic beacons and acoustic modems.

Fig. 5. ARIES (left) and Isurus (right)

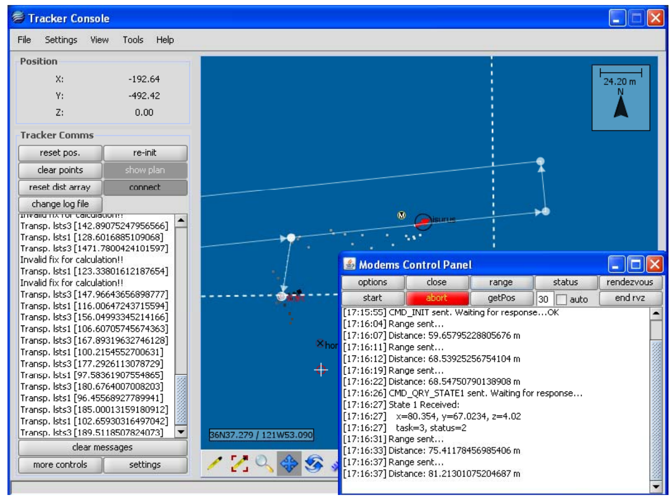

Fig. 6. Neptus Console during AUV mission execution.

While the vehicle is at the surface, it will continually send the estimated state using its Wi-Fi antenna. When the vehicle is submerged, its position can be monitored whether by querying it using the acoustic modem interface or by passively hearing the vehicle's acoustic beacons and merging this data with the knowledge of the acoustic transponders locations (defined in the mission map).

Isurus usually navigates using two acoustic transponders. The vehicle queries each transponder at a time, being a delay between queries and responses previously specified.

Whenever two consecutive acoustic queries are heard at the base, the vehicle position can be estimated by triangulating the vehicle distances to the transponders. The computed coordinates are added to the world state renderer in the form of a dot, being then possible to follow the mission execution in real-time.

The Isurus console also includes an acoustic modems control panel that can be used to monitor and control the mission execution. When queried, the vehicle will reply with the current maneuver state and its position. Through this control panel it is also possible to abort the mission execution, start and stop the rendezvous phase or use the modems' range functionality to estimate the distance between the vehicle and the base.

C. *Joint AUV operations*

An AUV rendezvous experiment involving both Isurus and ARIES was conducted at Monterey Bay on October 27, 2006. In this experiment, Isurus performed as the survey vehicle and ARIES performed as the server vehicle. The experiment utilized a time-optimal autonomous rendezvous algorithm developed at the NPS [18] and implemented on ARIES.

This rendezvous method considers a networked environment with one server vehicle and one or more survey vehicles, in which the server vehicle has a priori knowledge of the survey vehicles' mission profiles and may at any time be requested by one of the survey vehicles to rendezvous for data exchange. The server vehicle then performs the necessary path-planning to achieve the requested time-optimal or energy-optimal rendezvous.

The acoustic messaging protocol summarized in Table II supports this operation. A vehicle rendezvous is composed of two phases: approach, in which the server vehicle transits to an optimal point on the survey vehicle's planned route; and data transfer, during which the survey vehicle uploads data to the server vehicle. The rendezvous is triggered by the survey vehicle, causing the server vehicle to leave a loiter state and approach the survey vehicle, based on the knowledge it has of the survey vehicle's planned track. Upon completion of the rendezvous approach, the server vehicle prompts the survey vehicle to begin data transfer. After completing data transfer, the survey vehicle notifies the server vehicle and both vehicles resume normal operation.

Fig. 7 shows the vehicle positions and inter-vehicle messages exchanged at various stages of a rendezvous operation. The numeric labels refer to message interchanges described in Table II. Periodic modem range requests are omitted for clarity. The upper plot shows the modem interactions during the approach phase and initial part of the data transfer stage. The survey vehicle sends a *REQ* message and the server replies that it has begun *CLOSING*. Upon arrival at the rendezvous point, the server prompts the survey vehicle to *INIT RDVZ* and the survey vehicle begins data transfer (using the *CS* message). The bottom plot shows the vehicles in the data transfer phase (*RDVZ COMMS)* until the survey vehicle notifies the server that comms are complete (*CC*). The server vehicle finally acknowledges with a *RDVZ COMPLETED* message.

TABLE II
RENDEZVOUS MESSAGING PROTOCOL

Interaction messages	Originator	Data flow
(1) *REQ / CLOSING* (approach stage)	Survey Vehicle	Survey vehicle requests rendezvous, indicating its vehicle ID, current mission leg, and percent of current leg completed. Server vehicle acknowledges a rendezvous request and begins the rendezvous maneuver.
(2) *QUERY POSIT / REQ* (approach stage)	Server	If server vehicle reaches the expected rendezvous location but cannot establish communications with the survey vehicle, it requests a state update from the survey vehicle. The survey vehicle replies with an updated *REQ* message reflecting its current position.
(3) *QUERY POSIT TIMEOUT* (approach stage)	Server	If server vehicle does not receive a *REQ* message in response to its *QUERY POSIT* message within a specified time, the server vehicle terminates the rendezvous maneuver, notifies the survey vehicle, and returns to its loiter state.
(4) *RANGE* (approach and data transfer stages)	Either	The modem's ranging function provides an independent estimate of vehicle proximity in post-mission analysis. Future experiments can use this data as real-time feedback.
(5) *INIT RDVZ / CS* (data transfer stage)	Server	When server reaches expected rendezvous location, it prompts the survey vehicle to begin data transfer. Survey vehicle notifies server that data transfer has begun.
(6) *RDVZ COMMS* (data transfer stage)	Server	Server vehicle acknowledges *CS* message and will shadow survey vehicle until data transfer is complete.
(7) *CC / RDVZ COMPLETED* (data transfer stage)	Survey vehicle	Survey vehicle notifies server that data transfer is complete. Server vehicle acknowledges *CC* message and returns to loiter state.

V. CONCLUSION AND FUTURE WORK

A. *Evaluation*

A framework for the AUV communication and control was presented, and experimental results discussed. This is an important step towards the mixed initiative coordination control of heterogeneous vehicle systems for dynamically changing environments, combining the integration of operators in the planning and control loops.

B. *Future work*

We envision that the described infrastructure can evolve further with promising developments. Several items of future work are planned in relation to the use of underwater acoustic networks in several scenarios. In October 2007 we plan to conduct another set of experiments in the Monterey Bay. In these experiments the two vehicles are commanded to rendezvous prior to executing leader-follower maneuvers. The control loop will be closed through the acoustic channel. We are also planning to interoperate the acoustic and Wi-Fi networks so that operations with communication relaying through gateway buoys (or ASVs) can be achieved. Related research will focus on rendezvous and terminal homing of an AUV with an underwater docking station.

Recent developments in USTL such as Swordfish [4], an ASV for network-centric operations, and a new generation of AUVs like the Seascout AUV [19]-[20], will also guide future developments.

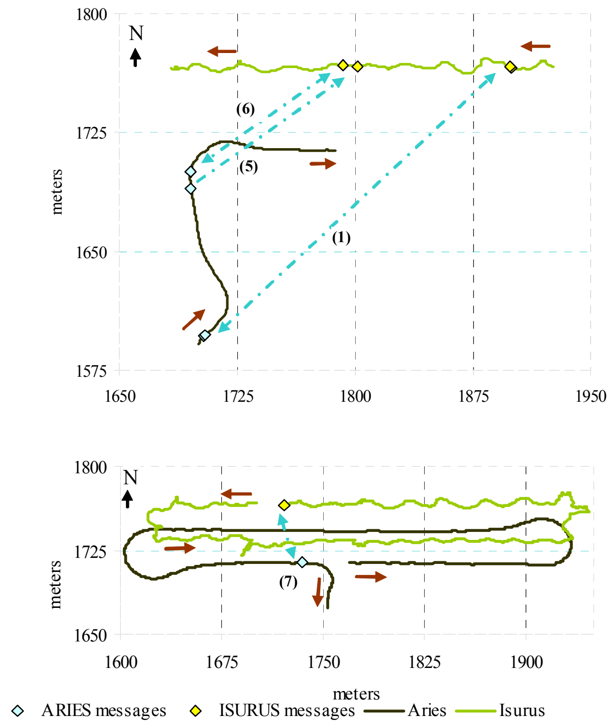

Fig. 7. Rendezvous mission plot: vehicle approach and rendezvous. Local grid with origin at reference location: 36º36.14'N / 121ºW 53.39'.

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REFERENCES

[1] N. Cruz, J. B. Sousa, F. L. Pereira, J. E. Silva, J. Coimbra and E. B. Dias, "Operations with multiple autonomous underwater vehicles: the PISCIS project", Second Annual Symposium on Autonomous Intelligent Networks and Systems (AINS'03), 2003

[2] D. B. Marco, and A. J. Healey, "Current Developments in Underwater Vehicle Control and Navigation: The NPS ARIES AUV", OCEANS 2000 MTS/IEEE Conference and Exhibition, pp 1011-1016, 2000

[3] Teledyne Benthos - Undersea Systems and Equipment, http://www.benthos.com

[4] H. Ferreira, R. Martins, E. Marques, J. Pinto, A. O. Martins, J. M. Almeida, J. B. Sousa, E. P. Silva, "Swordfish: an Autonomous Surface Vehicle for Network Centric Operations", submitted for publication in Oceans Europe'07.

[5] MaxStream, Radio Frequency modems, http://www.maxstream.net

[6] E. R. B. Marques., G. M. Gonçalves and J. B. Sousa, "Seaware: A Publish/Subscribe Communications Middleware for Networked Vehicle Systems", 7th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC'06), 2006

[7] J. Proakis,., E. Sozer, J. Rice and M. Stojanovic, "Shallow water acoustic networks", 2001 IEEE Communications Magazine 39(11), 114–119, 2001.

[8] C. Benton, M. Haag, R. Nitzel, D. R. Blidberg, S. G. Chappell, and S. S. Mupparapu, "Advancements Within the AUSNet (Autonomous Undersea Systems Network) Protocol", Proceedings of the Fourteenth International Symposium on Unmanned Untethered Submersible Technology, 2005

[9] Underwater Systems and Technology Laboratory, "Inter-Module Communication Library – version 2.0", http://whale.fe.up.pt/seascout, 2007

[10] C. N. Duarte, G. R. Martel, C. Buzzell, D. Crimmins, R. Komerska, S. Mupparapu, S. Chappell, D.R. Blidberg, R. Nitzel, "A Common Control Language to Support Multiple Cooperating AUVS", Proceedings of the Fourteenth International Symposium on Unmanned Untethered Submersible Technology, 2005.

[11] L. Freitag, L., M. Grund, C. von Alt, R. Stokey and T. Austin, "A shallow water acoustic network for mine countermeasures operations with autonomous underwater vehicles", Underwater Defense Technology (UDT), 2005.

[12] R. P. Stokey., L. E. Freitag, M. D. Grund, "A Compact Control Language for AUV acoustic communication", Oceans 2005 – Europe, Volume 2, Issue , 20-23 June 2005 Page(s): 1133 - 1137 Vol. 2, 2005

[13] P. S. Dias,, R. Gomes, J. Pinto, , S. L. Fraga, G. M. Gonçalves, J. B. Sousa and F. L. Pereira, "Neptus – A framework to support multiple vehicle operation", Today's technology for a sustainable future, OCEANS Europe 2005, 2005.

[14] J. Pinto., P. S. Dias, G. M. Gonçalves, R. Gonçalves, E. Marques, J. Sousa, F. Pereira, "Neptus – A Framework to Support a Mission Life Cycle", 7th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC'06), 2006

[15] P. S. Dias,., J. Pinto, G. Gonçalves, R. Gonçalves, J. Sousa and F. L. Pereira, "Mission Review and Analysis", Fusion2006, The 9th International Conference on Information Fusion, Florence, Italy, 10-13 Jul., 2006

[16] C. von Alt, , B. Allen, T. Austin and R. Stokey, "Remote Environmental Measuring Units", Autonomous Underwater Vehicle's 94 Conference, 1994.

[17] N. Cruz, L. Madureira, A. Matos and F. L. Pereira, "A versatile acoustic beacon for navigation and remote tracking of multiple underwater vehicles", MTS/IEEE International Conference Oceans 2001, 2001

[18] J. Nicholson, "Autonomous Optimal Rendezvous of Underwater Vehicles", Ph.D. Dissertation, Monterey, California: Naval Postgraduate School. 2004.

[19] J. E. Silva., B. Terra, R. Martins and J. B. Sousa, "Modeling and Simulation of the LAUV Autonomous Underwater Vehicle", submitted to 13th IEEE IFAC International Conference on Methods and Models in Automation and Robotics (MMAR'07), 2007

[20] Underwater Systems and Technology Laboratory , "Seascout AUV", http://whale.fe.up.pt/seascout