

AUVs as mobile nodes in acoustic communication networks: field experience at the UAN10 experiment

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Abstract— The UAN – Underwater Acoustic Network – project has among its goals the investigation of networked communication modalities in which mobile nodes are located in the environment in order to optimize the communication characteristics of the acoustic channel. The mobile network nodes in UAN are placed on Autonomous Underwater Vehicles (AUVs) carrying appropriate acoustic modems and capable of autonomous decisions. With this contribution we focus on the architectural design and implementation on AUVs of the “Folaga” class of a mission supervisor handling the communication, environmental sampling and decision making tasks, and reports the first results in terms of network communication capabilities as obtained in the UAN10 experimental activities that took place in the Tuscan Archipelago, Mediterranean Sea, in September 2010.

Sensor networks; Autonomous Underwater Vehicles; Acoustic Communication.

I. INTRODUCTION

Underwater acoustic communication is a hot research topic nowadays, since it is clearly seen as the enabling technology to establish a network of fixed and/or mobile underwater sensors. Application of such networks range from environmental, climate and pollution monitoring to off-shore industry to patrol and surveillance in security systems (both military and civilian). A range of scientific issues in underwater communication are investigated, for instance, in the special issue [1], and are reviewed in [2], where an extensive list of references is given. Within this research stream, the UAN – Underwater Acoustic Network [3] project was established in 2008, having among its goals the investigation of networked communication modalities in which mobile nodes are located in the environment in order to optimize the communication characteristics of the acoustic channel. The mobile network nodes in UAN are placed on Autonomous Underwater Vehicles (AUVs) carrying appropriate acoustic modems and capable of autonomous decisions. In particular, the AUVs must be able to autonomously react to changes in the environment (e.g., in oceanographic conditions) that affect the communication channel characteristics and to appropriately relocate themselves in order to guarantee some quality of service performance in the communication task. Moreover, the autonomous decisions must be taken in a distributed way, also in presence of lack of communication among the network nodes, and must in any case guarantee the fulfilment of a

general mission task, which in case of UAN is the surveillance around a critical asset. The above goals are indeed ambitious, and involve the development of appropriate both methodological and hardware/software architectural tools. From the point of view of distributed decision making in the UAN context, a cooperative algorithm has been designed, and its characteristics in terms robustness to node failures, communication delays, incomplete information are reported in a companion paper [4]. This contribution focuses on the architectural design and implementation on AUVs of the “Folaga” class [5] of a mission supervisor handling the communication, environmental sampling and decision making tasks, and reports the first results in terms of network communication capabilities as obtained in the UAN10 experimental activities that took place in the Tuscan Archipelago, Mediterranean Sea, in September 2010. UAN10 is an intermediate project activity with the goal of testing the different network functionalities in order to prepare for the conclusive experimental work scheduled for May 2011.

The paper is organized as follow: Section 2 describes the eFolaga AUV a specific class of Autonomous Underwater Vehicles used as mobile node of the network. In Section 3 we go into the detail of the mission supervisor software architecture giving details on its integration within the vehicle. Section 4 reports the field experience during the UAN10 experiment providing field data on the network performance. Finally, conclusions are given in Section 5.

II. UAN MOBILE NODES: THE eFOLAGA AUV

This paragraph gives a brief overview on the general characteristics of the eFolaga vehicles and on the modifications of the AUVs done in order to integrate them within the UAN network.

The most recent prototype of the vehicle class, the “eFolaga”, has an actuation system combining those of autonomous gliders with those of propulsion-driven AUVs. The vehicle navigates on the sea surface with its own propulsion system when in transit from one measuring station to another; it submerges vertically, exploiting ballast and attitude changes, when on station to perform the measurement. When at the surface, the vehicle has continuous GPS (Global Positioning System) contact and land-station contact through a mobile phone link or a dedicated radio link. The land station link allows for on-line modification of the mission requirements and for almost real-time data transmission. The motion in the

surge direction is due to propulsion jet-pumps or to a propeller (both options are available) at the vehicle stern, while steering in surge – sway plane is obtained through two lower power jet-pumps at the vehicle bow, transversal to the surge direction. Vehicle diving is obtained by combination of a buoyancy change and attitude change through the presence of a ballast chamber and a wormscrew mechanism to internally displace the position of the battery pack. The diving actuation system is similar to that of oceanographic gliders, though it has to be noted that the Fòlaga has no wings or other hydrodynamic surfaces and its intended dive is in the vertical plane at zero pitch. A summary of the main technical characteristics of the eFòlaga is reported in Table 1.

TABLE I. eFOLAGA MAIN CHARACTERISTICS

Diameter (m)	
External	0.140
Internal	0.125
Length (m)	2.000
Mass (Kg)	30.0
Mass variation range (Kg) (assuming water density 1031 Kg/m ³)	0.500
Range of moving mass displacement (m)	0.050
Energy storage	Lead acid batteries, 12 V, 72 Ah
Autonomy (hrs.)	8
Diving scope (m)	0 - 50
Break point in depth (m)	100
Speed	
knots	2 (jet pumps) / 4 (propeller)
m/s	1.01 / 2.02

To integrate the eFolagas within the UAN network a specific payload with dedicated hardware has been designed and implemented in order to connect the acoustic modem to the vehicle electronics. Figure 1 shows a view of the payload external structure with the protruding acoustic modem and CTD sensor. The main hardware of the payload is shown in Figure 1, right, and it is represented by a PC-104 board with serial lines to communicate with the modem and with the CTD probe which is available for continuous monitoring of the water conditions. Figure 2 shows the Fòlaga AUV with the UAN module mounted at mid-vehicle.

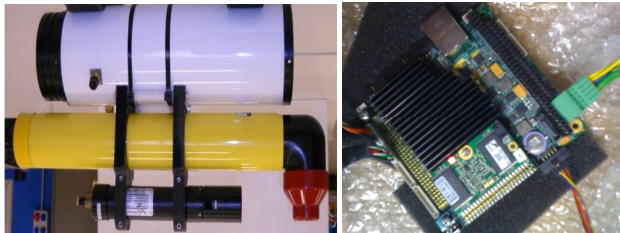


Figure 1. Left: UAN module with acoustic modem (from Kongsberg Maritime) and CTD. Right: Payload PC104 main board



Figure 2. Fòlaga AUV with the UAN module with the acoustic modem and CTD mounted at mid-vehicle.

TABLE II. PAYLOAD HARDWARE: MAIN BOARD CHARACTERISTICS

Item	Description
CPU	1GHz, VIA EDEN, Ultra Low Voltage
DRAM	1GB, DDR2, 533/400 on SO-DIMM socket
Chipset	VIA CX700M
Serial Ports	1 RS232 Full modem 1 RS232FM/422/485 Configurable
USB Ports	2 x USB 2.0
Hard disk	4 GB Internal Flash Disk

III. SOFTWARE ARCHITECTURE

From an architectural perspective, the goal is that of implementing a mission supervisor capable of interpreting and generating messages to the other network nodes, and to give commands to the vehicle native guidance, navigation and control (GNC) system. The approach followed is the “back-seat driver” paradigm, pioneered by the MIT group and co-workers [6 – 8]: the mission supervisor must be able to take decisions and give high level commands to the native GNC vehicle system, which is the sole responsible of the low-level execution of the commands. Similarly, the supervisor has to handle the communication tasks at the application level, while the lower level communication layers are left to the communication software implemented in the acoustic modem itself. In this way, conceptually depicted in Figure 3, it is possible to integrate in a modular way all the system components reducing (ideally regardless) the specific nature of the vehicle, of the acoustic modem and of the MAC and routing strategy of the communication network.

Communication at the mission supervisor level is handled through the MOOS system [5], a pub/sub middleware. The mission supervisor is implemented as an event-driven Mealy finite state machine, which generates an output based on its current state and input, and which is in itself a MOOS process able to establish a connection to a remote MOOS Database for sending and receiving acoustic messages.

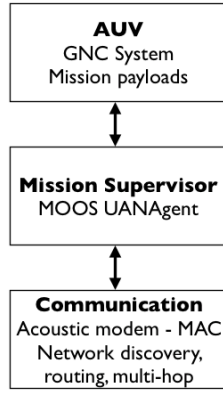


Figure 3. Conceptual architectural scheme of the implemented system

In particular, the mission supervisor, called UANAgent, extends the *CMOOSClient* class provided by the MOOS framework:

```
Class UANAgent: public CMOOSClient {
    bool OnNewMail(MOOSMSG_LIST& newMail);
    bool Iterate();
}
```

The method *OnNewMail()* collects all the acoustic messages received, and updates the data structures used by UANAgent; the method *Iterate()* specifies the main thread of the class, and implements the main operations, such as the overall control (from an application standpoint) of the acoustic communication and of the Folaga vehicle.

The logic of the mission supervisor is realized through a state machine composed by three states (IDLE, TASK, TEST) and two macro-states (MISSION, AUTO), as depicted in the state machine diagram shown in Figure 4. Each one of the states of the machine is related to a single task to be executed by the Folaga vehicle (e.g. Navigation task), a task to be executed by the MOOS pub/sub system (e.g. send a specific acoustic message), or a waiting condition. The two macro states allow the mission supervisor to execute complex and autonomous tasks, and in particular:

MISSION macro-state: the supervisor goes into this state to execute a desired mission, i.e. an ordered sequence of tasks for the Folaga AUV or for the MOOS pub/sub system. For example, a typical mission can include: a diving task to reach a desired depth followed by an underwater navigation task for a desired period of time while sending periodic notification on the vehicle status (e.g. battery level, depth, etc.) through the acoustic link.

AUTO macro-state: when in this state, the mission supervisor is able to adapt its behavior to changing environmental conditions, executing periodic samplings of the water column and moving to optimize the acoustic communication.

A. Interface to the Folaga

One of the most critical parts in the architecture described is represented by the interface between the mission supervisor and the Folaga existing software. For this reason, to maintain the maximum flexibility and separation between the mission supervisor and the Folaga GNC native system, a dedicated interface has been set up. Figure 5 shows the block diagram of the main processes running on the whole vehicle, both in the UAN payload and in the core of the Folaga. In particular, the following process and their counter parts on the vehicle support the mission supervisor and allows for the integration between the payload and the vehicle itself:

Folaga Controller: connects with the User Control Server on the Folaga. It is responsible for the delivery to the Folaga Control System of the commands issued by the MOOS Client main process for the control of the vehicle, and vice versa to communicate Folaga answers and/or errors to the mission supervisor.

Radio Controller: connects to the Radio Modem Client on the Folaga. It is responsible for receiving user commands when the Folaga is on surface. Through this process the payload can be configured and monitored in real time by the user.

Logger Client: connects to the Logger Server on the Folaga. It sends logs from the MOOS process to the Folaga, which in turn will send them via radio to the user, when the vehicle is on surface.

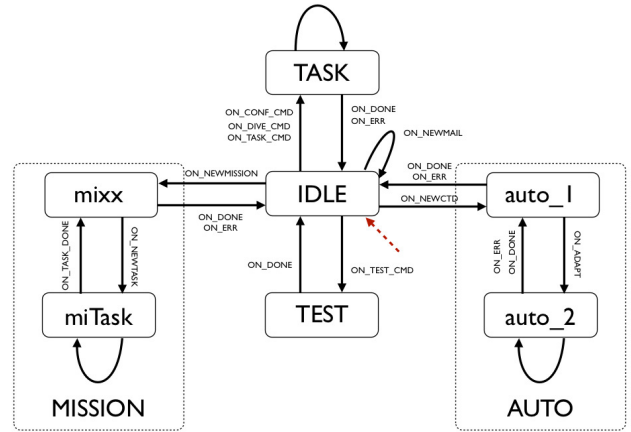


Figure 4. Conceptual representation of the mission supervisor state machine diagram. The red arrow indicates the initial state of the machine. The main events for each state are also indicated. The two macro-states, AUTO and MISSION, allow the machine to execute complex and autonomous missions.

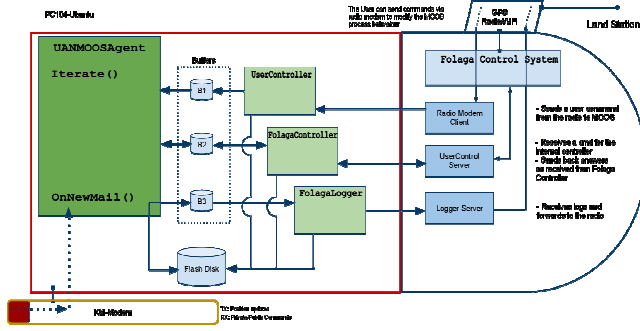


Figure 5. Interface between the Folaga vehicle and the UAN payload.

IV. UAN10 EXPERIMENT

This paragraph report results from field data as obtained during the UAN10 experiment where, in shallow water conditions, the vehicle and network functionalities were tested with up to two vehicles and two fixed nodes.

The experiment, held in Pianosa Island, Tuscan Archipelago, Mediterranean Sea, in September 2010 tested the underwater network for several hours, from the physical layer up to the MOOS application level. In particular, the physical layer of the network was represented by acoustic modems built by Kongsberg Maritime capable of transmitting up to 500bps and which also implemented the routing layer and multi-hop strategies. The network architecture was hence completed by the implementation of the PPP protocol to establish the IP connection, and on the use of UDP or TCP as transport protocols to allow the integration of the MOOS framework as application level. Seen from an application level, each node of the network was hence represented by a MOOS client (UANAgent) which was responsible for monitoring and managing the node status and behaviour and which connected to a central database for sending and receiving data.

During UAN10 experiment, which was an intermediate project activity with the goal of testing the different network functionalities, it was possible to record data sets relative to communication with MOOS pub/sub system configured and active, in the open sea. In particular, in this work we report results obtained on September 17 and on September 22 where all the network layers were tested with increased level of complexity.

The first test executed, on September 17 was a complete test in terms of network layers but with limited complexity in terms of network topology as only two nodes, one master and one slave were used. Figure 4 shows the nodes locations: the fixed node 1 (master modem) was located at 10 meters depth while the Folaga was navigating at full speed (2 knots) at surface, at 5m and 10m at varying ranges from 150m to 1000m. Figure 5 shows the CTD measurement obtained at the fixed master station location. Table 3 shows the network performance obtained on September 17, using the network in the master-slave configuration in terms of Round Trip Time and average packet loss percentage.

TABLE III. SEPTEMBER 17, 2010

Packet size		RTT (s)	Packet loss (%)
54 bytes	Average	7.107	17%
	Min	3.721	-
	Max	23.150	-
	Standard deviation	4.485	-
84 bytes	Average	9.151	14%
	Min	4.935	-
	Max	26.865	-
	Standard deviation	6.081	-
99 bytes	Average	12.795	33%
	Min	5.491	-
	Max	25.991	-
	Standard deviation	63.99	-

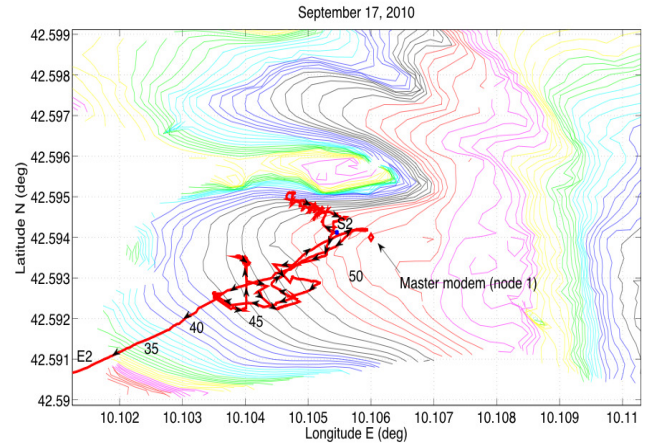


Figure 6. Master modem location and Folaga path on September 17, 2010. Arrows indicate Folaga direction along the route.

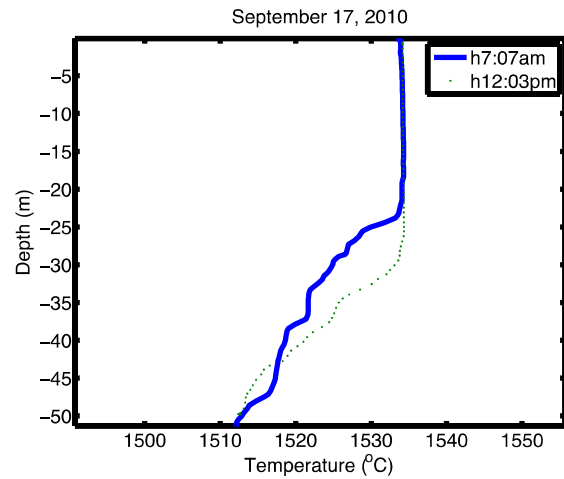


Figure 7. CTD casts taken on September 17, 2010, at location 42.5940N, 10.1071E

On September 22, true network connectivity was established among the master node, located again at 10 meters depth, and two slave nodes, one fixed, moored close to the sea bottom at 51m depth (anchored at the bottom, in a total of 58 m of water) and one moving node installed on the Fòlaga. Figure 8 shows the network topology during the experiment and the bathymetric contours. Figure 9 shows the CTD profile obtained at the master node location. The master node and the moving node were above the thermocline (the Fòlaga was actually always at the surface) for the whole test, while the fixed node, placed at the bottom, was always right below it. Two tests were performed. In the first test, which corresponds to the top-left and top-right part of the Fòlaga path, the network traffic was generated from the master node (node 1) to the fixed node 3, with node 2, initially positioned West of the line connecting the two fixed node, only acting as a bridge to establish a multi-hop connection. In this initial condition, it was not possible to correctly establish the network connectivity because of a too high packet loss on the physical layer. After this first attempt the mobile node was moved to the East of the line between the master node and the fixed node 3 and there was immediate success of the physical relaying of packets, and the consequence correct activation of the whole network stack. Table 4 reports in this last configuration the network performance in terms of RTT and average packet loss.

It is interesting to correlate these communication results with the environmental conditions: as it can be seen from Fig. 9, there was no significant change of the sound speed structure in the water column during the whole day. The sound speed profile measured during the test, with a strong thermocline approximately between 25 and 45 m depth, is always causing downward refraction to acoustic propagation, and interaction with the bottom. Looking at the bathymetry (Fig. 8), one can note that the fixed node has at its West a rather gentle upslope, and at its East a rather abrupt down slope. The Master node was always eastward with respect to the fixed node; when the Fòlaga was placed westward of the fixed node, it could not relay messages to the fixed node, while successful communication was achieved with Fòlaga on the eastward side of the fixed node. One possible explanation for this behavior is that in the eastward Fòlaga configuration there are less bottom multipaths from the Fòlaga to the fixed node with respect to the Fòlaga at the Westward situation. While this is only given as a conjecture at the moment of writing, requiring supplementary analysis which has not been completed yet, it is in any case evident that, at least in this case, combined effects of bathymetry and sound speed have indeed to be taken into account in order to optimize channel characteristics.

Finally, in the second test, all the nodes were sending and receiving in parallel, and again mobile node 2 was also acting as a relay between the master and the fixed node 3. Table 5 reports the network statistics in this case. It is possible to see an increase in the RTT and in the packet loss if compared with the first test due to packet collisions created by the traffic increase.

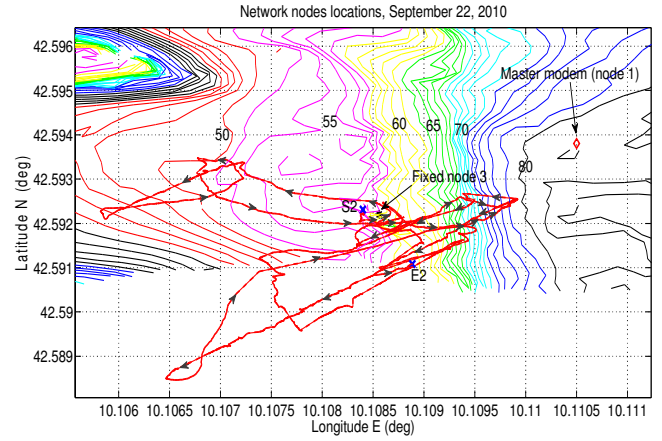


Figure 8. Network nodes locations on September 22, 2010. The Fòlaga path is shown overimposed on the bathymetric contours (main depth profiles in the area of interest are tagged) with the dashed line. Fòlaga started at location S2 and ended the mission at E2. Its orientation is indicated with the arrows.

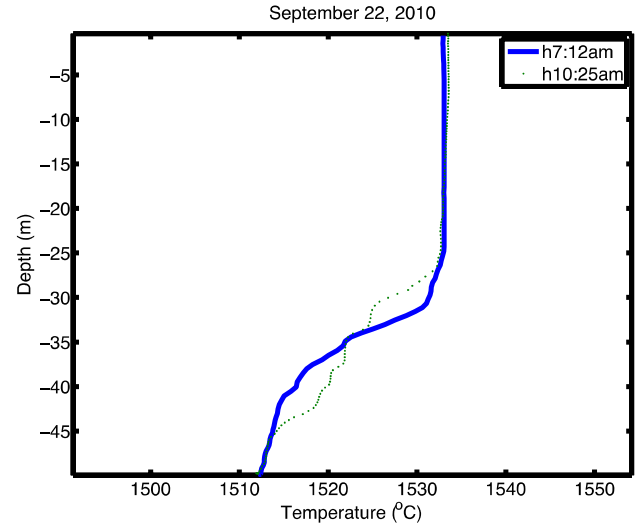


Figure 9. CTD casts taken on September 22, 2010, at location 42.5940N, 10.1060E

TABLE IV. SEPTEMBER 22, 2010 NETWORK PERFORMANCE (TWO NODES CONNECTED VIA MULTI-HOP)

Packet size		RTT (s)	Packet loss (%)
54 bytes	Average	15.432	20%
	Min	9.618	-
	Max	31.675	-
	Standard deviation	5.864	-

TABLE V. SEPTEMBER 22, 2010 NETWORK PERFORMANCE WITH THREE NODES.

Packet size	Network path		RTT (s)	Packet loss (%)
54 bytes	1->2	Average	23.794	58%
		Min	4.514	-
		Max	75.253	-
		Standard deviation	20.563	-
54 bytes	1->2->3	Average	45.947	34%
		Min	7.192	-
		Max	99.976	-
		Standard deviation	29.553	-

CONCLUSIONS

In the paper we described the architectural design and implementation on AUVs of the Fòlaga class of a mission supervisor handling the communication, environmental sampling and decision-making tasks for the integration of the autonomous underwater vehicle as a mobile node of an underwater acoustic network.

The paper reports the first results in terms of network communication capabilities as obtained in the UAN10 experimental activities that took place in the Tuscan Archipelago, Mediterranean Sea, in September 2010. UAN10 is an intermediate project activity with the goal of testing the different network functionalities in order to prepare for the conclusive experimental work scheduled for May 2011.

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