MOOS-IvP

Autononomous Communication, Command and Control Architecture for Distributed Sensing Networks

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Abstract

MIT is leading a multi-institutional, multi-disciplinary research effort aimed at developing PLUSNet, a new autonomous, distributed acoustic sensing network concept for persistent undersea surveillance in the littoral ocean. A major obstacle to the development of distributed sensing networks in the littoral is the inherent limitations of underwater acoustic communication, in terms of bandwidth, intermittency and latency, typically limiting communication to a few tens of bytes per minute, with intemittency and latency of order tens of minutes. To enable robust operation of the network MIT has developed and recently implemented a comprehensive Autonomous Communication, Command and Control (AC^3) architecture, inherently capable of supporting nested autonomy, where individual nodes and clusters of nodes can complete adaptive and collaborative sensing missions without operator control and intervention. Based on the open architecture MOOS-IvP robotic network control framework developed in a collaborative effort by MIT, University of Oxford, and NUWC, the **PLUSNet** architecture provides a generic framework for nested and autonomous, fully integrated sensing, modeling and control, which is directly adaptable to adaptive and collaborative sensing in other ocean observation networks with fixed and mobile assets, such as ORION. The MOOS-IvP framework was successfully implemented and demonstrated in the recent MB'06 experiment in Monterey Bay specifically aimed at demonstrating the network connectivity and the autonomous, adaptive tracking of an acoustic target by an autonomous underwater vehicle (AUV) equipped with a 100 m long towed array, as well as adaptive environmental sampling using a CTD. With the principal objective being detection, localization and tracking of a fast moving target, particular considerations were required to allow proper control while towing the array. Thus, mission related objectives were tempered by the need to consider the effect of a sequence of maneuvers on the motion of the towed array which cannot tolerate sharp bends or twists. A key to the robust satisfaction of such multiple objectives, characteristic of most autonomous operations is the behavior-based control model of MOOS, augmented with a novel interval programming (IvP) approach for performing behavior coordination using multi-objective optimization.

1 Introduction

1.1 Motivation

The primary motivation for designing an Autonomous Communication, Command and Control (AC^3) architecture for a distributed sensing is to achieve the ability to deploy a fleet of autonomous mobile marine platforms over a wide area of the ocean environment and over a long period of time with little or no human supervision. Concerns over effective coverage, communication range and safe operation of the platforms are all primary motivations of an effective form of autonomous control. The long duration and unpredictable nature of the environment require the vehicles to adapt their missions and behave autonomously as events unfold. Conversely, practical concerns of marine operations over large areas require an element of operator predictability over the course of time. These two characteristics can be at odds with each other in practice, but can be tempered by effective periodic communication through a network of fixed and mobile nodes co-deployed in a coordinated manner designed to balance individual platform and network objectives.

1.2 PLUSNet Undersea Surveillance Network

MIT is leading a multi-institutional interdisciplinary research effort toward the development of **PLUSNet** , a distributed network concept for persistant littoral surveillance, funded by the Office of Naval Research. The principal responsibility of MIT, in addition to acoustic sensing, modeling and processing, is the development and implementing a robust AC^3 architecture which is robust to the low bandwidth, intermittency and latency inherent to underwater acoustic communication, the major obstacle to robust operation of underwater networks. In the recently completed MB'06 experiment in Monterey Bay, the new infrastructure was implemented and demonstrated for the autonomous control of and communications with a network consisting of two Bluefin'21 AUV's, one outfitted with a dual line array in a 'swordfish' configuration, another towing a 19-element vector sensor array (Fig. 1). The **PLUSNet** concept envisions a number of gliders to serve as communication relays, and for performing persistaent environmental assessment, which together with a centralized ocean modeling and assimilation framework will allow the field and the individual nodes to autonomously adapt to the current environmental situation. In MB06 several gliders were deployed, but only one of these was equipped with an acoustic communication capability. Instead, to demonstrate the operation and control of a multinode network a fleet of four MIT-owned autonomous kayaks were included, all being operated using MOOS-IvP and thus compatible with the **PLUSNet** AC^3 infrastructure.. The communication to and from this and other deployed AUVs was achieved using fixed gateway buoys, equipped with acoustic modems. In addition to the implementation of the overall AC^3 framework, a comprehensive set of autonomous, adaptive behaviors were developed, which can be dynamically - interactively or autonomously - activated during long term deployment, through simple (32 bytes) acoustically transmitted messages from a ship or shore station. Similarly, whenever polled by the central field control, the AUV's will transmit status reports, and contact reports once a target was detected.

The towed vector sensor array is one of the main elements of this larger objective, which aims to exploit the latest advances in AUV technology to deploy an autonomous vehicles with endurance of the order of several months. A critical element of this approach includes sensor scalability to the smaller platform sizes afforded by AUVs and efficient energy use to obtain the required levels of persistence. A key component is the extensive use of adaptive and collaborative behaviors, compensating for the reduced sensing capabilities provided by the smaller acoustic apertures. Further, vector sensor technology facilitates scalability by virtue of its higher theoretical gain for a given aperture length.

1.3 Behavior-based Control

With the limited communication capabilities of an underwater network, the individual mobile nodes, as well as clusters of nodes, cannot be relying on centralized control. Communication may in periods be totally lacking, and even in most conditions being limited to a few tens of bytes every few minutes. Therefore, it is absolutely crucial to apply a nested autonomous command and control infrastructure, where the individual nodes and clusters are capable of operating fully autonomously. Thus in an acoustic surveillance system such as **PLUSNet** , the individual underwater vehicles must therefore be capable, based on very simple cues, if any, to perform all the sensing, modeling and control involved in achieving a full description of a fast moving target which may have penetrated the area once communication is reastablished. To achieve this, it is necessary to place a large amount of modeling and processing power, and artificial intelligence, in the individual nodes, making them capable of adaptively choosing behavior patterns which optimizes surveillance performance, without centralized operator control.

To achieve this, a higher level control architecture is required than that traditionally used for routine predetermined survey patterns traditionally applied on AUVs, e.g. for seabed mapping. This type of advanced robotic control is precisely the reason for the development of behavior-based autonomous control architectures and software infrastructure such as `MOOS-IvP` which is being applied in **PLUSNet** . In behavior-based systems, platform control is the result of set of independent, specialized modules working together to choose appropriate vehicle actions. It can be viewed as an alternative to the traditional sense-plan-act control loop where decision-making and planning are performed on a single world model that is built up and maintained over time. Commonly cited virtues of behavior-based systems include: the ease of development of the independent modules, the lack of a single complex world model, and the potential for a highly reactive vehicle with certain behaviors triggered by the appropriate events in a dynamic environment. The origin of these systems is commonly attributed to Brooks' "subsumption architecture" [1]. It has been used in a large variety of applications including: indoor robots, e.g., [2], [3], [4], [5], [6], land vehicles, e.g., [7], and marine vehicles, e.g., [8], [9], [10], [11], [12]. Action selection is the process of choosing a single action for execution, given the output of each behavior. Action selection has well known difficulties as reported in [5] and [7] for which multi-objective optimization is providing some countermeasure.

2 PLUSNet Autonomous Platform Control

2.1 The MOOS-IvP Autonomy Architecture

The PLUSNet AC^3 system is based on the MOOS-IvP architecture for autonomous control, developed and maintained under a GPL license by MIT, Oxford University, and NUWC. MOOS-IvP is composed of the Mission Oriented Operating Suite (MOOS), a open source software project for communication between, and nested control and coordination of, software processes running on the nodes of network of autonomous platforms. MOOS-IvP is fully portable and platform independent, but typically implemented under GNU/Linux. MOOS-IvP also contains the IvP Helm, a behavior-based helm that runs as a single MOOS process and uses multi-objective optimization with the Interval Programming (IvP) model for behavior coordination, [13]. See [14] and [15] for other examples of MOOS-IvP on autonomous marine vehicles.

A MOOS community contains processes that communicate through a database process called the MOOSDB, as shown in Fig. 2. MOOS ensures a process executes its "Iterate" method at a specified frequency and handles new mail on each iteration in a publish and subscribe manner. The IvP helm runs as the MOOS process `pHelmIvP` (Fig. 3).

Each iteration of the helm contains the following steps: (1) mail is read from the MOOSDB, (2) information is updated for consumption by behaviors, (3) behaviors produce an objective function if applicable, (4) the objective functions are resolved to produce a single action, and (5) the action is posted to the MOOSDB for consumption by low-level control MOOS processes. The specifics of the adaptive behaviors used in MB06 are described in Ref. [16]. Adaptive behaviors for oceanographic sampling with the autonomous kayaks are described in Ref. [17]

2.2 The Back-Seat Driver Paradigm

To allow the `MOOS-IvP` network control to be applied on a variety of fixed and moving nodes with different control software, a "back-seat driver" paradigm was adobted and integrated with the `MOOS-IvP` control software infrastructure. The idea is that all high-level control, including the adaptation to measured and estimated parameters, is performed in a payload computer (PLC) running MOOS-IvP. The PLC will also handle all communication with the network, either through a radio link while surfaced, or an acoustic modem when submerged. All lower level control, and basic navigation and platfom safety tasks are handled by the native vehicle control software running in the main vehicle computer (MVC), i.e. Huxley in the case of the Bluefin AUVs. The communication between the PLC and the MVC is performed over an ethernet socket,operated by a MOOS process pHuxley running on the PLC, as illustrated in Fig. 4. The commands passed to the MVC are simply continuous updates of desired heading, speed and depth, which the MVC then translates to desired rudder, thrust and elevator signals to the tail cone. The MVC will return current navigation and state data, which pHuxley will then publish in the MOOSDB. In the BF'21 vehicles operated in MB'06, the PLC incorporated a Linux-based CPU for general-purpose computational tasks, such as the multi-objective helm, as well as a specialized 8 GFlop vector processor to support heavy signal processing loads such as spectrum analysis and broad-band beamforming. In this architecture, the PLC appears to the MVC as a simple NMEA device, and vice versa. (NMEA is an industry standard for communication between marine devices.)

The basic safety tasks performed by the MVC include mission abort due to bottom altitude limit violations, and lack of commands from the PLC in a certain specified time, as well as an overall mission timeout. Higher level safety tasks such as exceeding the specified operating radius, and individual behavior timeouts or failures, are handled by the PLC.

2.3 The IvP Helm

The IvP Helm, as a software module, can be viewed as an interface between the set of behaviors and the MOOSDB and the other system components connected to MOOSDB. Its primary function at run time is to arbitrate between behaviors by soliciting objective functions from each, over a common decision space, and performing multi-objective optimization. Besides posting the resulting decision to the MOOSDB, the helm also posts other variable-value pairs based on requests of the behaviors generated during the behaviors' function-producing iteration. This includes state information that one behavior may communicate to another across iterations, such as a condition that marks the completion of one behavior and triggers the activation of another.

The helm, upon startup, reads a configuration, i.e., mission, file with sets of parameters. An important component of our research objectives is to allow behaviors to be adaptive not only to environment events, but also to periodic direction from field control. This means a mission file is not a static script with a start and completion, but more aptly described as a state space with an initial state and conditions for migrating between states based on events; mission-control, environment or otherwise.

2.4 Autonomy States and State-Transitions

The vehicle mission specification used in **PLUSNet** is comprised of a set of states, behaviors operating in those states, and events from the field and **NaFCon** for transitioning between states. The states are shown in Fig. 5 and described below.

`DEPLOY-STATE:` Entered on receipt of the DEPLOY message. The vehicle transits to its deployment location and begins to loiter waiting for a prosecute message.

`PROSECUTE-STATE:` In this mode, the vehicle transits toward the currently estimated current position of the target. If the vehicle gets within a predetermined range of the estimated target position, it begins a loiter maneuver waiting for an acoustic detection. If an acoustic detection is made, the vehicle will maneuver to track the target until it moves outside its operational area, it loses the target, or a RETURN or ABORT message is received.

`ABORT-STATE:` The vehicle will transit toward its abort waypoint. If the waypoint is reached, a SURFACE message will be generated and the vehicle will enter the SURFACE state.

`SURFACE-STATE:` SURFACE: The system initially begins in this state waiting for a DEPLOY message. The SURFACE message is also internally generated when the vehicle reaches either its return or abort waypoints.

`RETURN-STATE:` The vehicle will transit toward its return waypoint. If the waypoint is reached, a SURFACE message is generated and the vehicle will enter the SURFACE state.

Each state is comprised of one or more vehicle behaviors responsible for achieving the objectives of that state.

3 PLUSNet Network and Field Control

A key component of an operational network of autonomous mobile marine sensing platforms is the interface to the operators for overall field control and strategical and tactical asset allocation. In **PLUSNet** this function as managed by **NaFCon** , the Network and Field Control (**NaFCon**). In MB06 **NaFCon** was located in an office on shore, but in the netcentric context, it could be alternatively located anywhere in the world, on shore, on a ship or an aircraft, or for that sake on a dedicated underwater vehicle. Thus, for example in MB06 it was convenient to simulate **NaFCon** on the research vessel, or in situations where acoustic communication was unreliable, onboard the AUV itself. With its modular structure, MOOS directly lends itself to such flexibility, as illustrated in Fig. 6, where the **NaFCon** control can be switched between shore, the R/V New Horizon, and the AUV Macrura.

Due to the limited bandwidth, and the latency and intermittancy, of the underwater communication network, the amount of data that can be transmitted to and from the field assets is extremely limited. Thus, the MB06 communication network was limited to nodes transmitting 32 byte messaces when polled, typiccally once per minute. Similarly the nodes can each receive a 32 byte command string at best once a minute. The `MOOS-IvP` network control was therefore designed to operate with only two classes of messages. **NaFCon** messages are commands sent to the nodes for redeployment, procecution of a target, or the execution of an oceanographic mapping mission. Communication from the nodes include status reports regarding battery status, navigation data etc., and in case a target is being prosecuted, information regarding the detection, classification, localization and tracking (DCLT) status.

3.1 The WHOI Acoustic Modem and NAFCON Interface

The AUVs are equipped with acoustic modems from the Woods Hole Oceanographic Institute (WHOI) that implement an adaptive decision feedback equalizer with integrated Doppler and error-correction to afford 80-bps frequency hopped-FSK mode communications. The modem provides the user with the tools necessary to create a simple time-division, multiple-access (`TDMA`) network for master-slave polled systems, or a random-access peer-to-peer network. Each communication transaction includes a short network packet called a cycle-initialization. This specifies the source, destination and data rate of the packet to follow.

A dedicated, compact Control Language (CCL) developed by WHOI is used to handle all underwater communication in **PLUSNet** . Thus, two primary types of messages are sent by **NaFCon** to the AUV; `DEPLOY` and `PROSECUTE` . The `DEPLOY` message instructs the AUV as to where it should operate for efficient use of the field. The message includes latitude, longitude, and depth of deployment. The `PROSECUTE` message is sent from **NaFCon** when a target of interest has been detected and localized to an area of uncertainty. The goal of the prosecution is to better localize, classify or track the target. Similarly, the AUV reports to the NAFCON by sending status reports, contact reports and track reports, coded into `PLUSNET_MESSAGES`.

The CCL messages received by the modem are decoded by the `MOOS` modem driver (iMicro-modem) and published as a variable in the MOOSDB (`NAFCON_MESSAGES`). The `pNafcon` MOOS process subscribes to the `NAFCON_MESSAGES` string variable and extracts details of the message sent by the **NaFCon** . Based on the message contents, `pNafcon` publishes mission control messages and set flags in the MOOSDB to allow the helm to activate relevant behaviors.

4 MB06 Adaptive Mission Examples

The results reported in the section are from field exercises in Monterey Bay in August 2006. The tow platform for the series of experiments described was an MIT 21 inch diameter, 158 inch-long AUV custom built by Bluefin Robotics in Cambridge Mass (Fig. 8). The vehicle possessed a single ducted thruster capable of propelling the vehicle and array at better than 3 knots. The navigation system of the vehicle consisted of a GPS receiver (for surface fixes), a Leica digital 3-axis fluxgate compass, Crossbow Attitude and Heading Reference System (AHRS), and bottom-locking RDI- Teledyne Workhorse Navigator 300 kHz Doppler Velocity Log (DVL). Dead-reckoning was achieved by fusing the above sensor inputs via a proprietary Bluefin algorithm.

One 0of the AUVs, Macrura, was towing a vector sensor array (VSA), which was designed to support a speed range from 0 to approximately 4 knots. Zero speed operation, wherein the array floats up behind the vehicle (which may be bottomed), invites the possibility of low-power detection modes and extended endurance. The particular VSA tested in MB'06 consisted of 47 meters of light-weight tow cable with integral optical fiber communications, an 8 meter vibration isolation module (VIM), 30 meters of acoustic array, and 15 meters of stability-enhancing drogue. See Figs. 8 and 9. In engineering the array and its mechanical interface to the Bluefin 21 vehicle, particular attention was payed to the issue of stability, which is typically poor for low-tension (low-drag/low-speed) systems of this type. Such instabilities are well known to be speed dependent and, in this case, dictated the selection of array materials in addition to a restricted maneuvering envelope for the AUV.

The tow cable section of the VSA was composed, in part, of a thin steel tube surrounding fiber optic data cables. This array section was thought to be vulnerable to damage if twists or kinks were to occur during operation. The following describes two deployments using the MOOS-IvP autonomy module. The results from both deployments are shown, together with results of the corresponding simulations that preceeded all MB06 missions, in Figs. 10 and 11.

5 Oceanographic Event Capture

Although the principal objective of **PLUSNet** is the detection, classification, localization and tracking of submerged targets such as submarines, in a coastal environment, the `MOOS-IvP` AC^3 framework lends itself doirectly to the autonomous and adaptive capture of the episodic oceanographic events that are among the core new capabilities privided by ORION. Thus, **PLUSNet** itself is exploiting the oceanographic environment for enhancing performance. For exampleseveral of the standard **PLUSNet** behaviors are directly aimed at measuring the sound speed distribution, with particular focus on episodic events such as internal wave solitons, upwelling, and fronts, which all are critical to the acoustic performance of both the sensing and the acoustic communication.

One such behavior in the standard **PLUSNet** set is an 'adaptive yo-yo' survey. Among the tools available to **NaFCon** for field control and asset allocation is a comprehensive modeling and assimilation framework, centered around the Harvard Ocean Prediction System (HOPS) and the acoustically focused environmental sampling framework AREA (Adaptive Rapid Environmental.Assessment), developed at MIT. On a daily basis, the HOPS/AREA framework will inform

NAFCON about regions with large sonar performance prediction uncertainty due to forecasting of upwelling, frontal activity or internal wave solitons. Fig. 12 shows an example of a forecast of the uncertainty of the acoustic transmission loss associated with internal wave activity. The 'posteriori uncertainty' shows the reduced transmission uncertainty predicted if an AUV is performing an adaptive tracking of the thermo-cline using the 'adaptive yo-yo' behavior. This behavior takes as its starting point a traditional yo-yo survey by the AUV equipped with a CTD oscillating between a minimum and maximum depth. However, whenever the AUV detects the depth of the strongest gradient, the thermocline, it will terminate the survey depth below and above whenever the local gradient falls below a specified ration of the maximum measured.

This particular mission was demonstrated succesfully in MB06, with the adaptive depth history of the AUV shown in Fig. 13. A typical sound speed profile in the operational area is shown in Fig. 14, showing the strong thermocline, here at 8 m depth. The accurate knowledge about the depth of the thermocline is particular critical gto communication performance, which is significantly improved if both source and receiver are below this depth, which due to internal wave solitons and upwelling may vari several tens of meters..

Other environmental assessment behaviors in the **PLUSNet** suite include an adaptive 'zig-zag' behavior, used to track a coastal front. This behavior is basically a horizontal version of the adaptive yo-yo described above.

5.1 Adaptive Sampling with AUVs in ORION

It is envisioned that ORION nodes in both the Pioneer Arrays, and the cabled regional and coastal observatories will be equipped with dockking units for one or more AUVs, significantly extending the coverage, but also allowing, through adaptive sampling and behaviors, rapid responce to episodic oceanographic events similar to those addressed in **PLUSNet** .

One can envision a single docking unit serving as re-charging station for several AUV's deployed around the node in a low-power mode, e.g. grounded on the seabed, or simply drifting at a specified depth through active bouyancy control. Once an event is detected or forecasted, the scientists operating the node can then activate one or more of the 'dormant' AUVs using simple acoustically communicated commands similar to those used in **PLUSNet** .

Using the `MOOS-IvP` architecture this control can be performed by the scientific community without any significant traing, through a dedicated GUI built on the same principles as **NaFCon** , and using direct adaptation of the **PLUSNet** CCL protocol, which has ample flexibility for incorporating 10-20 diffent adaptive and non-adaptive oceanographic mapping behaviors and event capture missions.

At the same time, more advanced users will be able to develop their own dedicated behaviors, using the standard `MOOS-IvP` toolset.

As a partner in the ORION CI team, MIT will work with the scientific community in identifying and developing the advanced behavior suite for oceanographic event capture, as well as a suite of safety behaviors which will eliminate or reduce the risk of the general user damaging the mobile assets and the fixed node facilities. Further, MIT will develop and maintain the ORION Adaptive Sampling GUI. Finally, MIT woill work with all manufacturers and operators of mobile ORION assets on integrating with the `MOOS-IvP` command and control infrastructure using the 'back-seat driver' paradigm.

With its modular structure, `MOOS-IvP` lends itself directly to simulatingall missions prior to field deployment. This is illustrated in Fig. 6 where the `MOOS-IvP` environmenta and mission files can be operated in a computer R/V New Horizon, simply by simulating the lower level command and dynamic control of Huxley. Thus for example, before the **NaFCon** operators were allowed to send commands to the submerged vehicle they had to demonstrate the robustnes by issuing the same commands to the simulation environment onboard R/V New Horizon.

For safety reasons it must be required that all ORION users intending to use the interactive, mobile assets must demonstrate the safe behavior in a `MOOS-IvP` simulation environment, whwre the assets are 'operated' in a 'virtual ocean', generated using the available modeling and assimilation frameworks. During the development of **PLUSNet** , MIT nas made extensive use of such a simulation framework, using HOPS for generating the virtual ocean, and all the 'yo-yo' and 'zig-zag' missions described above were tested extensively in simulation before their deploynment in

6 Summary

MIT is leading a multi-institutional, multi-disciplinary research effort aimed at developing PLUSNet, a new autonomous, distributed acoustic sensing network concept for persistent undersea surveillance in the littoral ocean. A major obstacle to the development of distributed sensing networks in the littoral is the inherent limitations of underwater acoustic communication, in terms of bandwidth, intermittency and latency, typically limiting communiction to a few tens of bytes per minute, with intemittency and latency of order tens of minutes. To enable robust operation of the network MIT has developed and recently implemented a comprehensive Autonomous Communication, Command and Control (AC^3) architecture, inherently capable of supporting nested autonomy, where individual nodes and clusters of nodes are capable of completing adaptive and collaborative sensing missions without operator control and intervention. Based on the open architecture MOOS-IvP robotic network control framework developed in a collaborative effort by MIT, University of Oxford, and NUWC, the **PLUSNet** architecture provides a generic framework for nested and autonomous, fully integrated sensing, modeling and control, which is directly adaptable to adaptive and collaborative sensing in other ocean observation networks with fixed and mobile assets, such as ORION. In the recent MB06 experiment the new control infrastructure was successfully implemented, controlling an autonomous underwater vehicle towing a 100-meter vector sensor array, as well as other autonomous underwater vehicles and surface crafts. The autonomous communication, command and control framework is based on a novel method of behavior-based control using multi-objective optimization and a novel set of vehicle behaviors that were demonstrated in field exercises to effectively control an AUV under different mission circumstances over hours of operation. As far as we know, MB06 provided the first ever demonstration of such a system on a physical marine platform.

In addition to the command and control architecture in itself, several of the adaptive behaviors developed and demonstrated in the **PLUSNet** context either directly apply or are easily adapted to capture time-critical, episodic oceanographic events, one of the principal objectives of the ORION observatory network. Thus, if, as envisioned, ORION nodes are equipped with docking units for one or more AUVs, the infrastructure and behavior suite developed for **PLUSNet** and demonstrated in MB06, may be directly adapted to allow an oceanographer from the comfort of his own office to issue high-level `DEPLOY` and `PROSECUTE` commands to one or more of these vehicles, which will the fully autonomously track internal wave fields or the development of a coastal front, for example, without the need for supervisory expert command and control.

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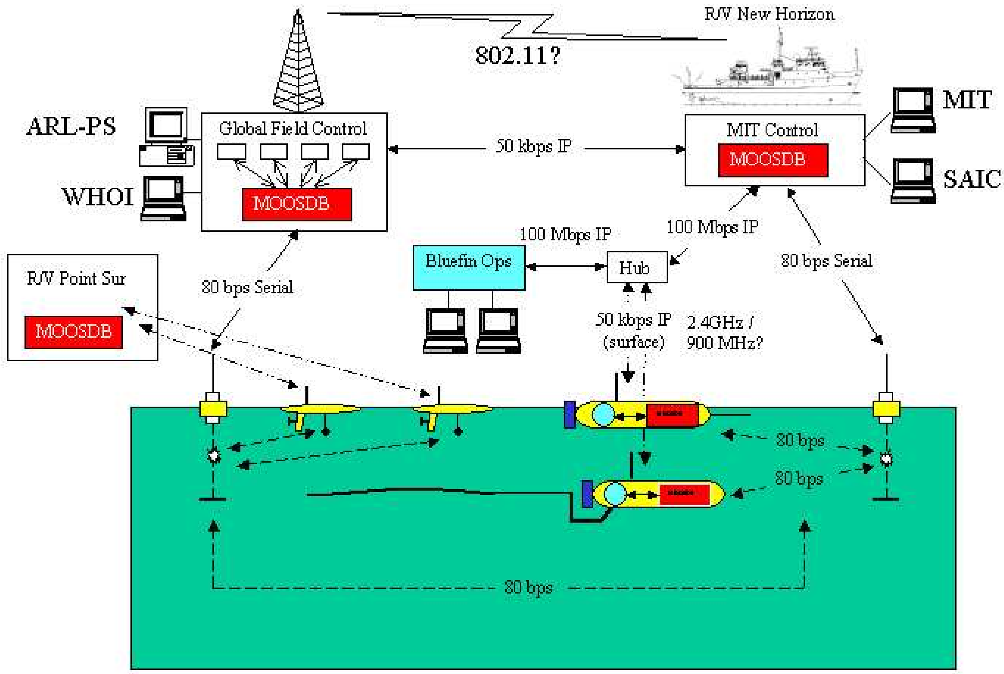

Figure 1: MB06 autonomous network. Two BF21 autonomous underwater vehicles were deployed and operated. One vehicle is equipped with a vector sensor array (VSA) to provide contact and track solution information to be shared via acoustic link to other AUVs and back to shore via a gateway buoy, which itself could be mobile, e.g. an autonomous surface craft, such as the autonomous kayaks deployed in MB06. The VSA-equipped node or platform may also be redirected by other nodes via acoustic link to deploy in another region based on information obtained by other nodes. The VSA-equipped vehicle is responsible for efficiently meeting its deployment obligations while avoiding sets of maneuvers that would compromise the safety of the sensing and communication structure of the array.

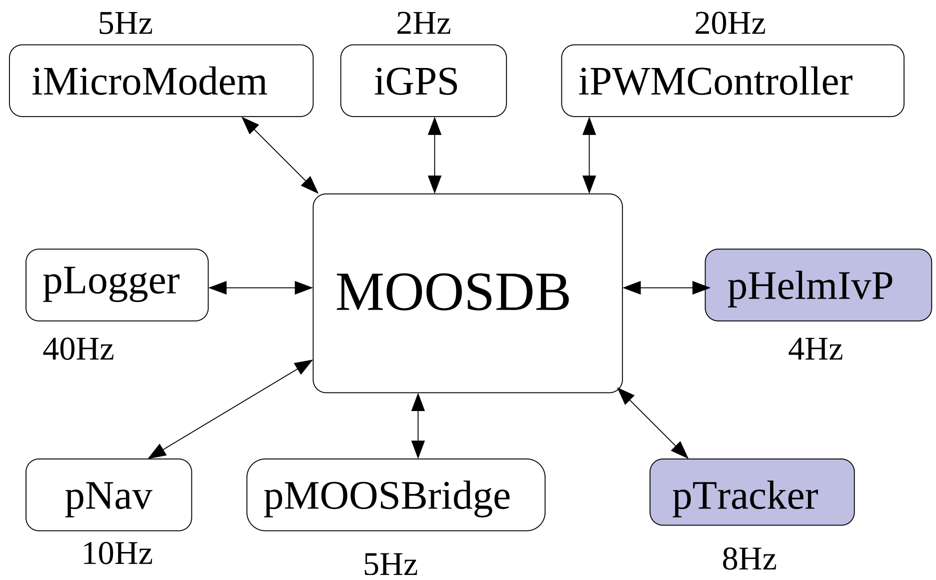

Figure 2: MOOS Community. All communication between processes is handled through the MOOSDB, using a mail 'publish' and 'subscribe' convention

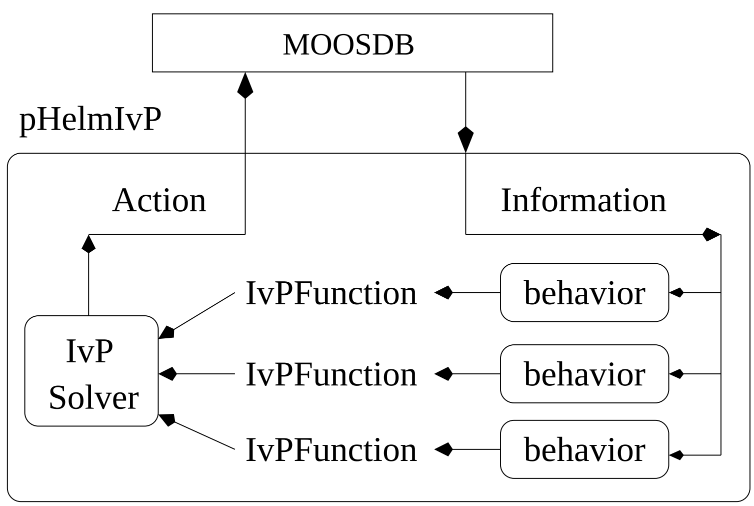

Figure 3: The IvP helm runs as a process called `pHelmIvP` in a MOOS community. MOOS may be composed of processes for data logging (pLogger), data fusion (pNav), actuation (iPWMController), sensing (iGPS), communication (pMOOSBridge, iMicroModem), and much more. They can all be run at different frequencies as shown.

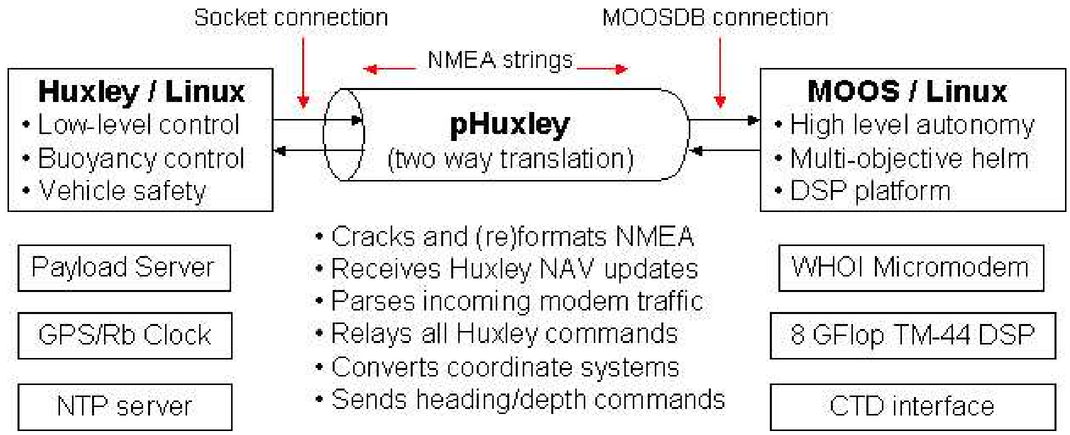

Figure 4: Schematic representation of the 'back-seat driver' paradigm, where higher level adaptive control and network communication is handled by `MOOS-IvP` on the payload computer, while lower level control, navigation and vehicle safety is handled by the main vehicle computer using the native control software.

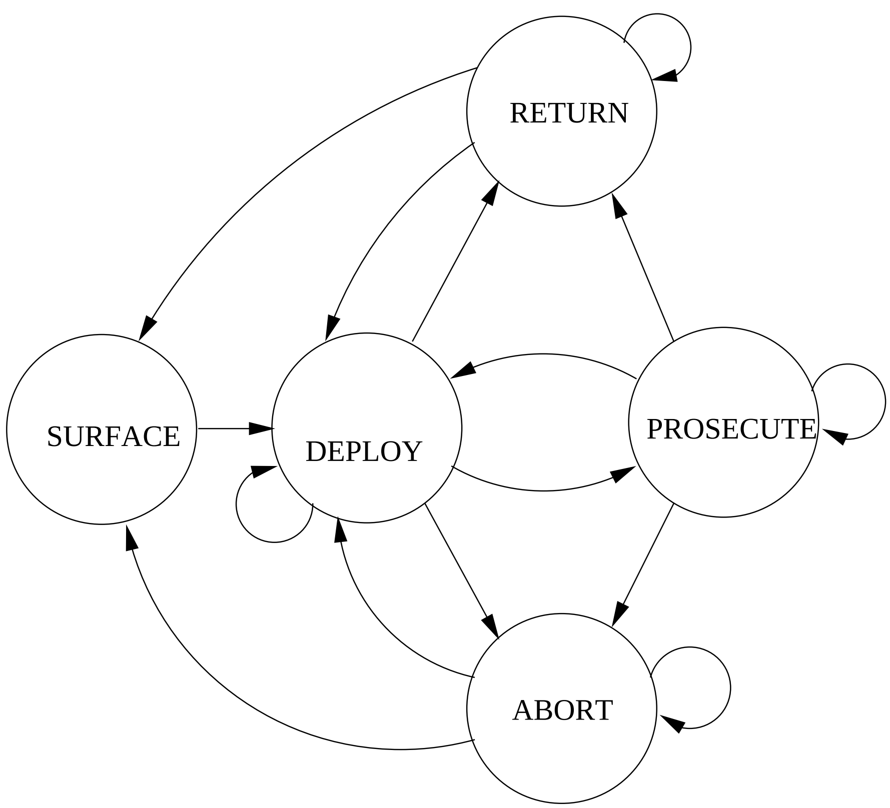

Figure 5: The five main vehicle autonomy states. Each state is transitioned into with the receipt of a NAFCON message of the same name. Each state is comprised of one or more vehicle behaviors responsible for achieving the objectives of that state.

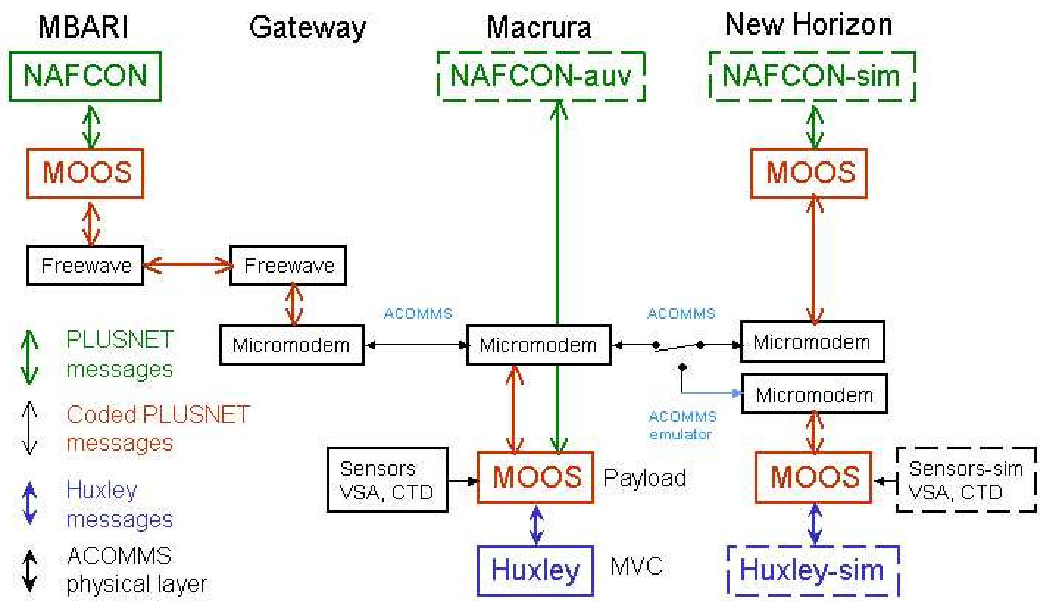

Figure 6: MOOS AC^3 infrastructure for AUV Macrura and R/V New Horizon in MB06. Communication with the **NaFCon** operators is packaged into CCL (command and control language) messages of 32 byte length. **NaFCon** messages are commands sent to the nodes for redeployment, procecution of a target, or the execution of an oceanographic mapping mission. **PLUSNet** messages are status reports from the nodes regarding battery status, navigation data etc., and in case a target is being prosecuted, information regarding the detection, classification, localization and tracking (DCLT) status.

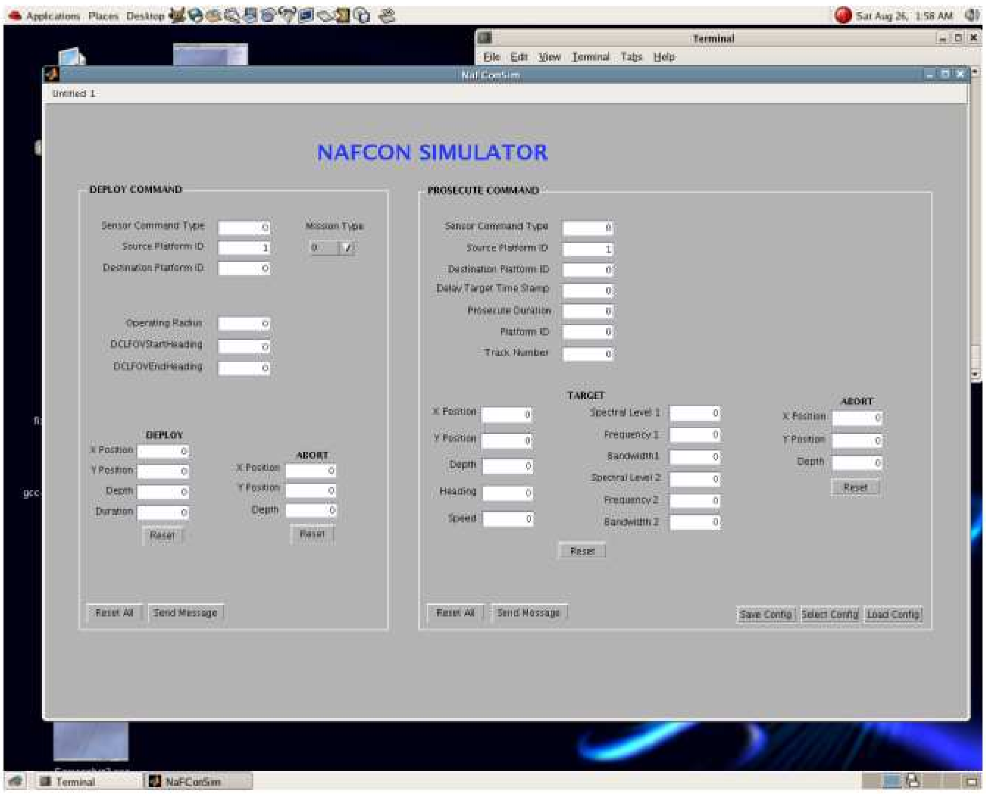

Figure 7: **NaFCon** operator interface used onboard R/V New Horizon for generating deployment and prosecute commands to submerged BF21 AUV's through acoustic modem.

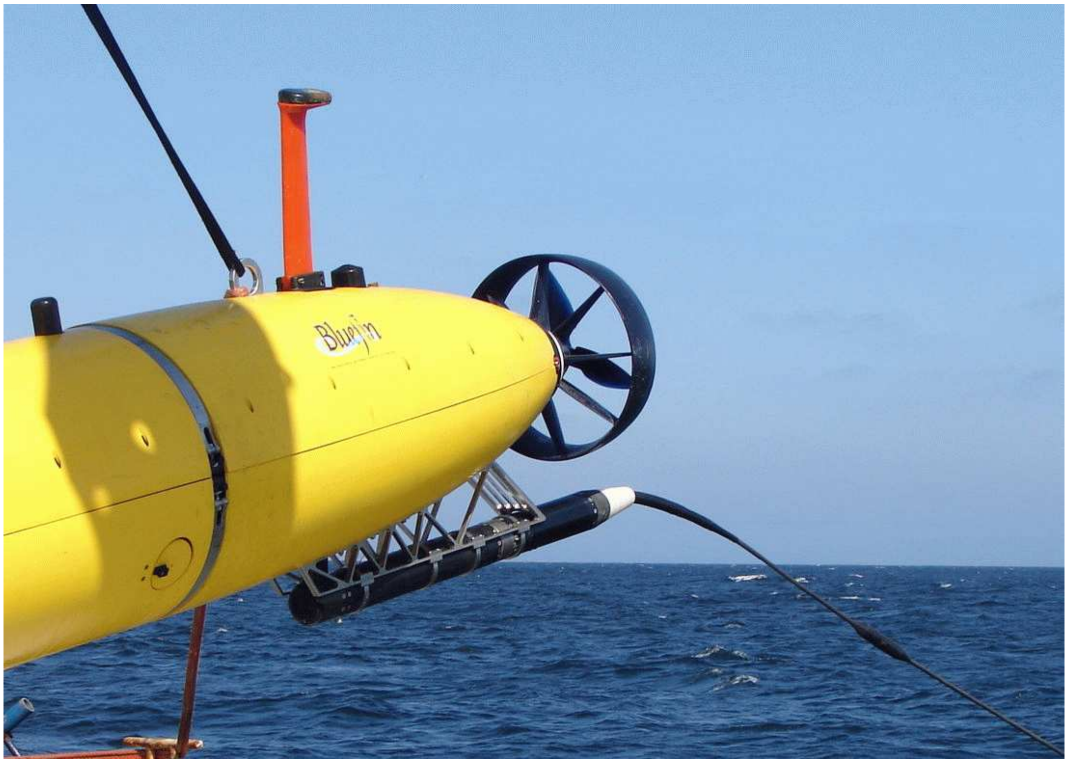

Figure 8: The MIT 21-inch Bluefin autonomous underwater vehicle modified to tow a vector sensor array. Photo from Monterey Bay exercises August 2006.

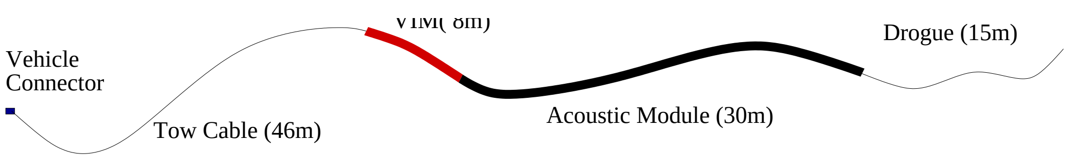

Figure 9: The vector sensor array is roughly 100 meters in total length composed of four sections leading out from the AUV: a 47 meter tow cable section, an 8 meter vibration isolation module, a 30 meter acoustic module, and a 15 meter drogue at the end.

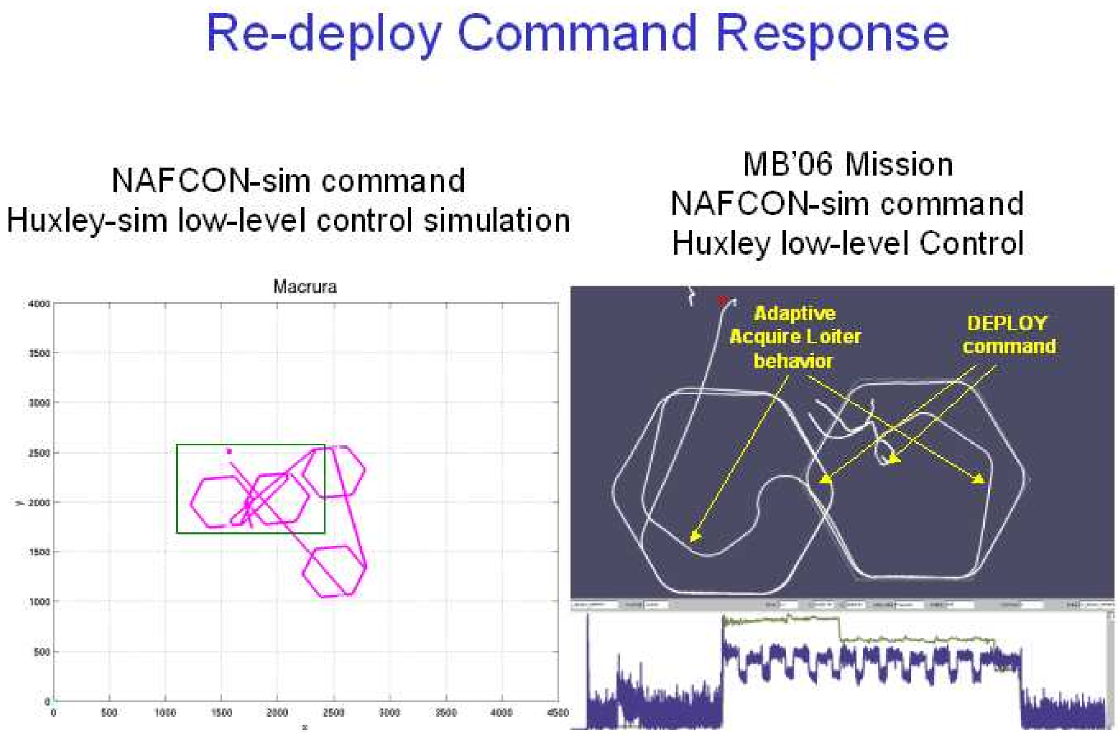

Figure 10: Monterey Bay deployment of MIT 21-inch Bluefin AUV towing a vector sensor array. After completing a hexagon loitering pattern following an initial deployment command, the AUV as sent a **NaFCon** message from R/V New Horizon, requesting redeployment to a hexagon pattern 500 m further west. Note the gradual spiralling into the new loitering pattern, controlled by a `MOOS-IvP` adaptive behavior limiting the array turn radius, Also, note the periodic speed change to improve acoustic communication performance. The left frame shows the results of simulations performed prieor to deployment, using exactly the same `MOOS-IvP` behaviors and processes, except for the pHuxley being replaced by a simple dynamic simulation of the AUV low-level control and response.

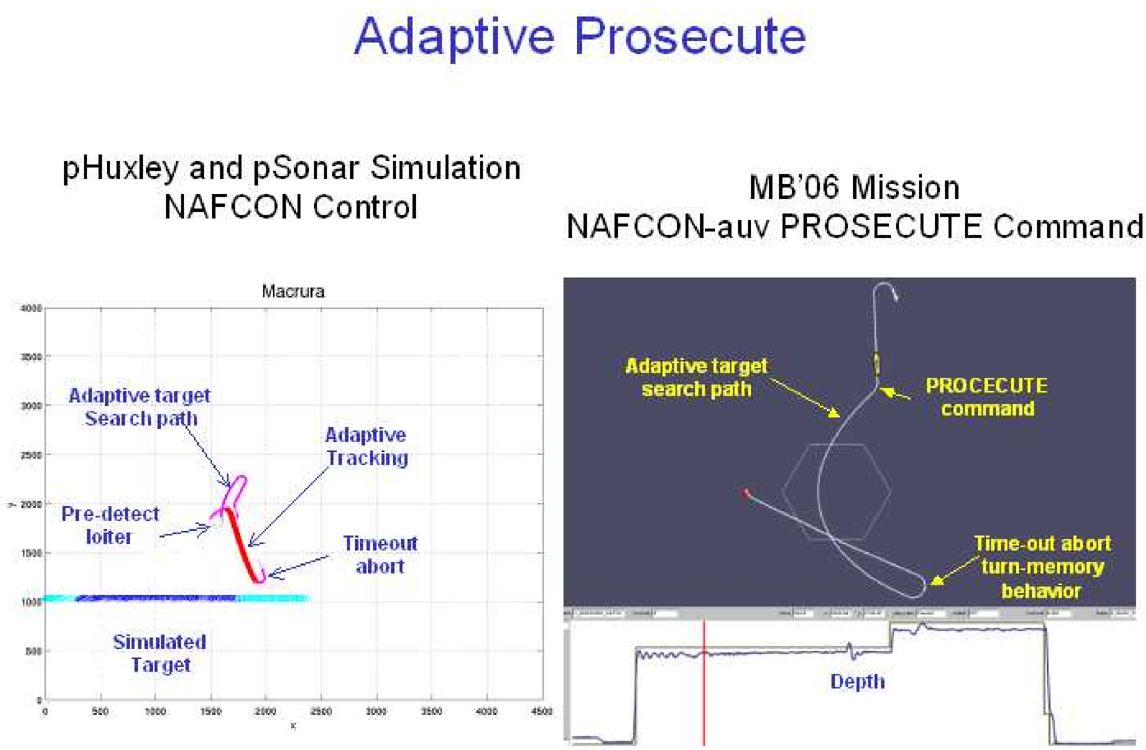

Figure 11: Monterey Bay deployment of MIT 21-inch Bluefin AUV towing a vector sensor array. The vehicle is initially commanded to deploy to a loiter patter. During transit it was at 8 meters of depth and cycling between speeds of roughly 1.2 m/s and 0.7 m/sec as shown by the depth and speed plots below. Before it arrived on station at the loiter region, it received a new message from field control via acoustic link to prosecute a contact on an easgterly heading, 2 km south of the AUV position. The vehicle then enters the prosecute phase for roughly 5 minutes. The desired speed of the vehicle is higher in the prosecute phase to close range quickly. After the vehicle has been in the prosecute phase for roughly 13 mins, without succesfully being detected the contact is opening range, and the mission is timed out. Then the vehicle proceeds to it's abort point, where it surfaces. The frame to the left shows the results of the simulation of the same mission, where the target was succesfully detected and tracked by the AUV using an adaptive behavior maintaining the relative target bearing close to broadside, optimizing the tracking performance.

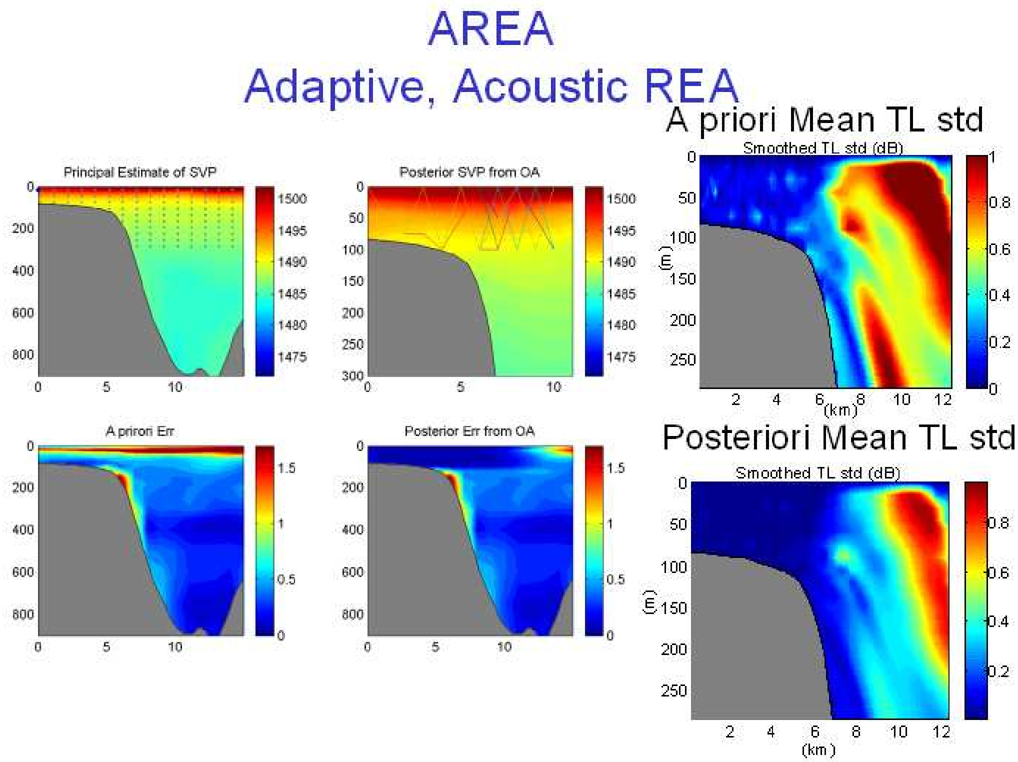

Figure 12: Adaptive Rapid Environmental Assesment in MB06. MOOS/AREA sonar performance prediction framework used to identify adaptive sampling strategy for internal wave field forecasted to enter operational area.

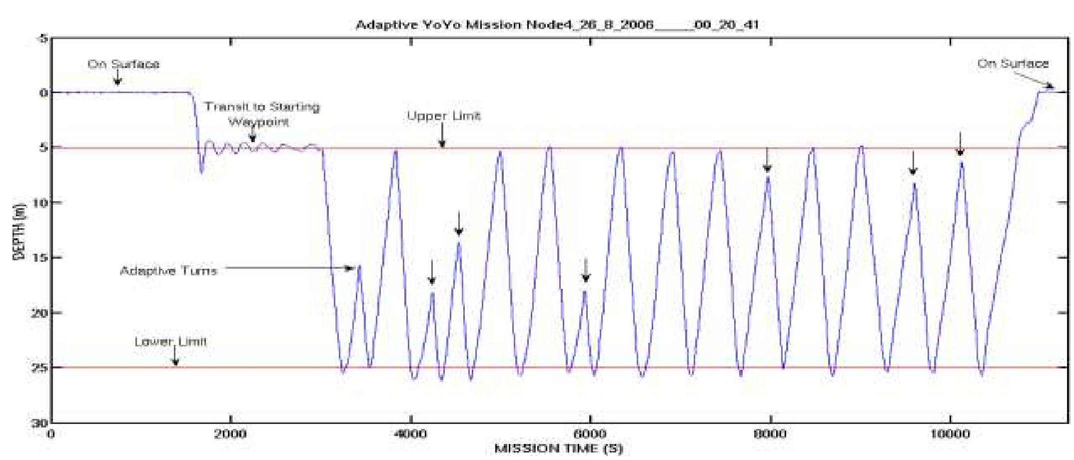

Figure 13: Adaptive yo-yo **PLUSNet** behavior applied to sample thermocline in MB06.

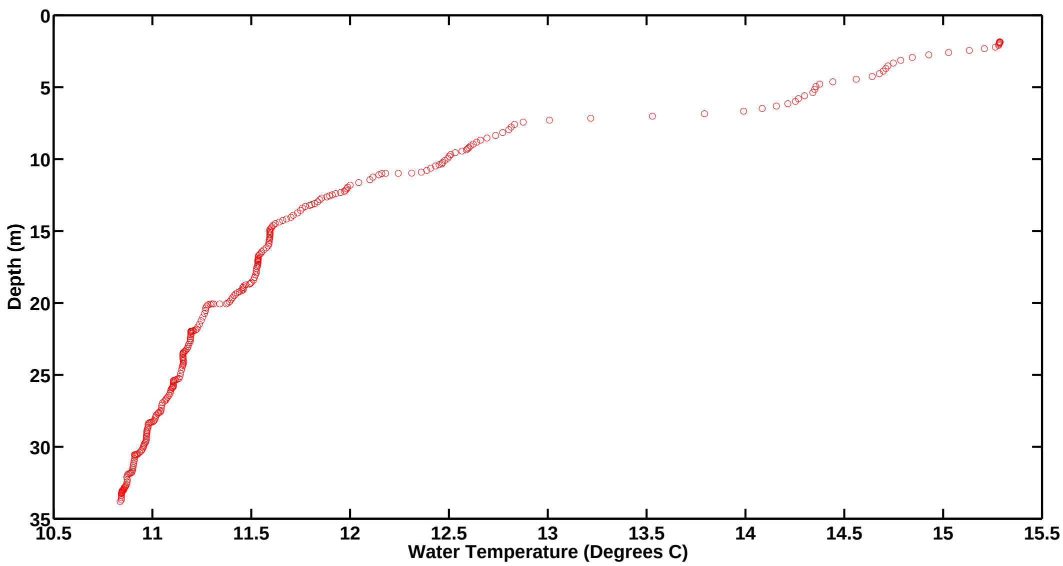

Figure 14: Sound speed profile measured by CTD lowered from a kayak, south of Santa Cruz in **PLUSNet** operational area.