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Autonomous Underwater Vehicles: An Application of Intelligent Control Technology

A. J. Healey[1], A. M. Pascoal[2], F. Lobo Pereira[3]

[1]Naval Postgraduate School, Monterey, CA. 93943,
[2] Instituto Superior Technico, Av. Rovisco Pais,1096 Lisboa Codex, Portugal
[3] Universidade do Porto, Rua dos Bragas, 4099 Porto Codex, Portugal

Abstract This paper provides an overview of some of the missions and vehicle control functionality being considered for the rapidly developing technology of Autonomous Underwater Vehicles. Spawned from the availability of small embedded processors and the increasing capabilities of underwater communications, these small untethered vehicles are expected to play a role as a force multiplier in expanding our ability to survey ocean areas. Missions expected to become viable in the near future include environmental monitoring, underwater inspection, geological survey as well as the current focus on military missions in mine countermeasures and remediation.

This paper gives an outline of the functionality required of such vehicles and their relation to intelligent control technology, some implementation details, and the future needs for research that continue to drive our field toward a practical reality. A list of references is given for readers interested in this subject.

1. INTRODUCTION

While the more conventional ROV has now found a strong niche in offshore operations and in Ocean Science, as exemplified by the Ventana and the Tiburon vehicles at MBARI [1], it is connected to a surface ship through an umbilical providing power and signal commands at high frequency so that human pilots can interact directly with the vehicle actuators (thrusters) in directing its motion. At the heart of the AUV technology is the driving need to eliminate this umbilical (tether) that currently connects the ROV machine to its operator. The tether - especially for deep water operations - is a tail that wags the dog. Drag forces from the tether must be carried by thrust from the vehicle, forcing vehicle designs to go larger in power, size and weight. Even in shallow water, the power cable will limit the horizontal range of survey to the point where a low cost AUV with endurance of several hours at low speeds of 3-8 knots would reduce ship time and be of significant use [2].

Many recent workshops and conferences have been devoted to the likely commercial and scientific potential for the use of AUV technology. Born from military requirements for stand-off weapons and remote sensing, and coupled with the rapid commercialization of microcomputer technology, it is now possible to foresee some civilian use for AUVs in ocean science, offshore operations, environmental monitoring and underwater inspection [3].

2. MISSION SCENARIOS

Coupling free swimming to the ability to receive commands at low rate (even 300 bps) and send data at a faster rate (claims to 10Kbps at 10 km. range [4]) with reliability (uncertain at present), leads to a plan to construct an Autonomous Ocean Sampling Network [5]. In this scenario, ocean sampling which is currently performed by surface ships and towed bodies together with fixed placement sensor buoys would give way to an adaptive sampling network of mobile sensors that increase the sampling resolution and allow for time / space correlated oceanographic data recovery. The concept places a vehicle as a mobile node in a network of fixed nodes that communicate acoustically for navigation data, commands and data retrieval. By using multiple vehicles in a coordinated formation, ocean sampling for CTD and dissolved oxygen, and turbidity [6] would be made to respond to rapidly emerging 'events' being adaptable upon command from a remote site as the data is being analyzed. In this context, spatial areas are considered to be in the range of 2km. by 2km. with a 'rapid' response being in the order of hours rather than weeks to months as it is at present [7].

A second mission scenario undertaken by the European Economic Community within the MAST program is to perform seabed survey for water quality and video imagery in coastal waters that are subject to chemical pollutants with the attendant damage to the plant and animal life forms. For this purpose, the Marius vehicle [10], has been conceived and constructed, and is undergoing sea trials in Lisbon. Figure 1 illustrates the Marius vehicle which would be one of a multiple of these seabed survey vehicles, launched to transit to the survey site and flying at a defined nominal height above the seafloor taking video recordings where commanded.

Yet at third mission class, under study at MBARI and Woods Hole involves video, sonar, water quality, methane concentration surveys around underwater hydrothermal vents for times during their activity as well as revisiting for comparative analysis during times of inactivity. This scenario requires the rapid deployment of small AUV's with capability to navigate to the site, perform sonar / video inspections, move around the area of interest under limited and high level command from the operator, and return to a home position for recovery.

The critical features that involve control technology include, underwater navigation, high level command and control through acoustic communications, precision motion control of the vehicle, coordinated control of vehicle control modes, vehicle / manipulator interactions, and enhanced reliability through redundancy and autonomous adaptive reconfiguration with inbuilt failure diagnostics and error recovery [8].

The ability to automatically garage the vehicle to a fixed underwater location, download data and receive power would significantly enhance the mission utility of these vehicles but has not yet been clearly demonstrated.

3. FUNCTIONALITY REQUIRED

The basic functional diagram for a typical AUV is depicted in Figure 2, which captures part of the functional organization of the NPS Phoenix [9] and the Marius [10] vehicles The following systems and respective interconnections can be identified:

Vehicle Support System (VSS) - The Vehicle Support System controls the distribution of energy to the electrical and electromechanical hardware installed on-board the vehicle and monitors its energy consumption. This system is also in charge of initializing all sub-systems and during operation, detecting basic hardware failures, and of triggering emergency reflexive maneuvers whenever required (e.g., upon detection of a leak in a pressure container, it triggers a surface by inflating a lift bag).

Actuator Control System (ACS) - The Actuator Control System is responsible for controlling the speed of rotation of the propellers and the deflections of the control planes in transit (bow and stern planes and rudders). Actuator set points are provided by the Vehicle Control System in response to a mission data file resident in the Coordination (Tactical) level software as part of the Mission Control System.

Navigation System (NS) - The Navigation System provides estimates of the linear position and velocity of the vehicle, as well as of its orientation and angular velocity. This system merges information provided by a Positioning System (a long baseline unit with a network of transponders) and a Motion Sensor Integration System. The motion sensor package will typically include the following units:

i) - rate gyros, pendulums, accelerometers and fluxgate compass or gyrocompass;
ii) - flowmeter;
iii) - depth cell;
iv) - echo sounders;
v) - doppler log.

The outputs of the Navigation System are fed back to the Vehicle Guidance and Control System.

Vehicle Guidance and Control System (VGCS) - The Vehicle Guidance and Control System accepts as inputs reference trajectories issued by the Mission Control System (Coordination Level) and navigational data provided by the Navigation System. It outputs commands to the Actuator Control System (set points for the speed of rotation of the propellers and deflection of the control planes) so that the vehicle will achieve robust, precise trajectory following in the presence of shifting sea currents.

Acoustic Communication System (ACOMS) - The Acoustic Communication System is a bilateral digital acoustic link that is used by the operator to send new mission directives to the Mission Control System, and by the vehicle to relay back information regarding its status. Typically, short messages would be sent across the acoustic channel, such as sensor readings, mission requested user commands and user requests for data. For operation in shallow waters, the main difficulty facing this system is to achieve communications at distances exceeding 3km. in the face of multipath propagation, rapidly changing acoustic channel characteristics and Doppler shift.

Mission Sensor System (MSS) - The Mission Sensor System collects data from a suite of environmental sensors that measure conductivity, temperature, pressure, turbidity, fluorescence, oxygen contents and pH. On the Marius and Otter [11] video cameras provide close-up images of the seabed. The Phoenix, Ocean Voyager, and Odyssey, [12] include high frequency sonar. Selected data can be stored for post-mission analysis.

Mission Control System (MCS) - Based on a plan provided by the user, the Mission Control System automatically sequences and coordinates the execution of those tasks that are required to achieve that mission, together with inbuilt recovery to vehicle and mission level faults discussed in the next section. It embodies the equivalent of a mission finite state machine with coordination level functions called the Strategic and Tactical levels in the Phoenix architecture

4. CONTROL ARCHITECTURES

The systematic design of control software for Autonomous Underwater Vehicles requires new methods and concepts to deal with dynamic systems where interactions between discrete events and continuous time vehicle response signals play a crucial role. The lack of a well established theory to tackle this problem spurred the growth of a large number of approaches based on methods and concepts and concepts that borrow from various fields ranging from Artificial Intelligence, Robotics, Computing and Software Engineering Sciences to System and Control Theories, and Intelligent Control. The last field has been emerging as a generalization of Control Theory in order to manage complex systems in uncertain environments by using cognitive engineering systems and the power of available hardware and software technologies. The complexity associated with the number and diversity of functions thatmust be performed requires careful consideration od possible architectural design options.. We limit ourselves in this section to the main entries of a generally accepted taxonomy of conceptual architectures.

1. Purely reactive approaches advocating the absence of a planning mechanism. These approaches implement control strategies as a collection of condition-action pairs, relying on the definition of a hierarchy of behaviors representing reactions to internal or external stimuli. These systems maintain no internal state, perform no search and rely on a direct coupling between sensors and actions and a fast feedback loop. Inspired by studies from the field of ethology on animal behavior, the subsumption approach proposed in [13] avoids the use of an explicit world model and implements both primitive and complex behavior by a more direct coupling between perception and action relying on the definition of a hierarchy of behaviors [14]. These behaviors represent reactions to internal or external stimuli without any planning activities or anticipating the consequences of the resulting actions. In [13], it is argued that apparently purposeful action can arise from the competition of layered behaviors according to a predetermined priority scheme. Tests of layered control for AUVs indicated that the complexity of the architecture increases significantly with the number of required behaviors. In order to overcome the performance sensitivity among actuating behaviors, a state configured form of layered control is proposed [15]. This architecture adds a high level of control in the form of a state table which determines the vehicle state by configuring the layered control structure. This architecture has been implemented in the MIT AUVs Sea Squirt and Odyssey [16].

2. In contrast with subsumption-like architectures, hierarchical schemes include well defined planning and control mechanisms [17]. A centralized world model is used for verifying sensory information and generating actions in the world so that, based on some assumptions on the real environment, mission goals are achieved. Control of the mission execution is performed by an entirely independent system. Two main sub-classes may be considered:

1. Classic - In these systems the planning module fully pre-determines the activities required to achieve a certain goal based on some assumptions on the real environment. In [18], it is outlined a control structure composed of three interacting hierarchies of task decomposition, world model and perception. Knowledge of the past, present and projected future are used in each of the planning, modeling and information processing components of the hierarchy. This paradigm is best represented by hierarchical architectures like NASREM [18] which encompass the purpose of enforcing modularity and a software methodology. This structure was instantiated in the MAUV project where two AUVs were constructed. A six level control system architecture of task decomposition, world modeling and sensory processing was designed and constructed [19]. In [20], an analytic formulation of such systems based on the principle of increasing intelligence with decreasing precision is proposed. Such an intelligent machine is structured in three levels: Organization, Coordination and Execution, [21]. One distinctive characteristic of this approach arises from the notion of task composition of primitive functions.

2. Systems of Reactive Planning - In these approaches, planning and execution are interdependent. No implementation has been referred to in the literature. In [17] and [22] a three level hierarchic architecture is implemented. A temporal planner generates a plan which is transformed into a sequence of actions by the second level of the architecture. This level is also responsible for controlling the execution. There are two different control loops closing during execution: At the coordination level, where both execution monitoring takes place during the normal course of operation and error handling in exceptional situations. At the functional level, where execution modules are activated whenever the accomplishment of the task at hand is within the reach. The feedback law guarantees robustness via functional reactivity. In [23], a Reconfigurable Control Architecture is proposed in order to extend the reactivity so that the management of onboard resources is encompassed. For a given context arising during execution, this control structure seeks the most adequate recruitment of on-board resources to carry out the task.

3. Hybrid: - By employing a reactive system for the lower level control and a planner for the higher level decision making, this approach offers a compromise between the previous main approaches (e.g.. [24], [25]). The control system is separated into two or more communicating but independent units. While the lower level reactive processes take care of the immediate safety of the vehicle, the higher level uses the planner to generate the sequence of actions. The Rational Behavior Model (RBM) [9] is a tri-level hierarchical architecture based on three levels of abstraction, called the Strategic, the Tactical and Execution levels respectively, that has been implemented in the Naval Postgraduate School AUV. The role of the Strategic level is to organize complex behaviors reflecting user selected mission commands and, in this process eliminate potential conflicts which may otherwise arise in the data driven low-level reactive activities. In [24], the SSS architecture is presented. This three layer architecture, as in RBM, combines servo-control, "subsumption" and symbolic layers. The system is based on the definition of appropriate interfaces between the three layers. The first interface is the command transformation between the subsumption layer and the corresponding servos. The command interface between the symbolic and subsumption layers is responsible for the parametrization of certain modules and selecting which behaviors are on or overiden. A further modification of layered control was presented in [26]. This is an heterarchical structure, since information is processed by the various modules individually, and coordination of their activities takes place by exchange of commands. A command arbitration protocol is also proposed that, based on a measure of acceptability of alternative commands produced by the various modules, optimizes the actual vehicle command. In this class the control architectures developed in [27] and [28] may be included.

4. Behavior-based Architectures - In [29], the behavior-based architecture also referred to as reactive subsumption-style approach is presented. These systems embody some of the properties of the purely reactive systems but also require some form of internal representation in order to decide what action to take. A common property of these systems is their distributed nature: they consist of a collection of parallel concurrently executing behaviors, devoid of centralized coordinator.

5. IMPLEMENTATION

Implementation aspects and vehicle design are exemplified by the 'Odyssey' vehicles of the MIT Sea Grant program [12], the 'Ocean Voyager I and III' [6], the 'Marius' vehicle [10], which are seagoing operational vehicles for ocean survey, and as control systems testbeds, the NPS 'Phoenix' vehicle [30] and the MBARI 'Otter' [11].

These vehicles and their configurations are described in recent papers devoted to AUV technology [31]. The control system for the NPS Phoenix is based on a Gespac embedded processor running the OS-9 real time multitasking operating system with sensor interfaces through A/D, timers, serial and parallel interfaces to the control surface and thruster motors, inertial sensors, and sonars. Mission control is accomplished through a second system of processors in a poolside SUN Sparc station, and SGI IRIS workstation linked in a LAN through ethernet connections. In the near future, the LAN will be internal to the vehicle and the mission control software layers will be in a second embedded processor running the VxWorks real time operating system

While no single method for designing the mission control functions have emerged at this point, it is generally accepted that some form of a tri-level software architecture will be required for missions that are more complex than a simple 'fly around a race track' mission. Mission control logic for the 'Phoenix' is encoded in 'PROLOG' rules coupled to the servo level control functions through a set of "C" coded tactical level functions. These retain the numerical data aspects of the mission plan, perform numerical computations on vehicle response data, and return Boolean decisions as responses to 'PROLOG" queries and commands. In this way, a convenient separation of the symbolic / numerical computational interface is implemented for the signals required to service the finite state transitions occurring during rule query..

6 FUTURE RESEARCH NEEDS

Future needs for research continue to be in the areas of underwater navigation, communications, reliability, and control. In control, the needs are seen to be NOT in performing simulation studies with the various multitudes of servo level stabilization methods available today, but in the development of vehicle intelligent behavior, the coexistence of discrete event and continuous dynamic systems, and above all, evaluation of system performance in the underwater environment. Also, problems with the latency and uncertainty of real sonar signals either from image sonars or Long Baseline (LBL) navigation signals, continues to demand new tactical level software techniques for their handling in timely fashion. Enhancing the precision of navigation with GPS / INS / LBL complementary filtering is in continuing need of further investigation particularly for use with real time low cost embedded processors. Also, the whole question of the reliability of vehicle performance in the underwater environment with real sensors is not yet known.

7. ACKNOWLEDGMENTS

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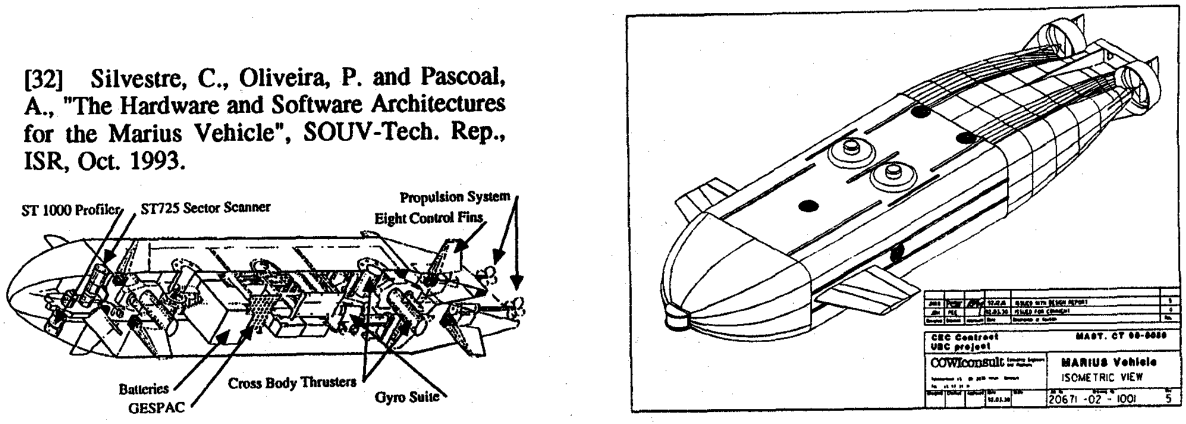

Figure 1 Sketches of the NPS Phoenix (left) and the Marius (right) Vehicles

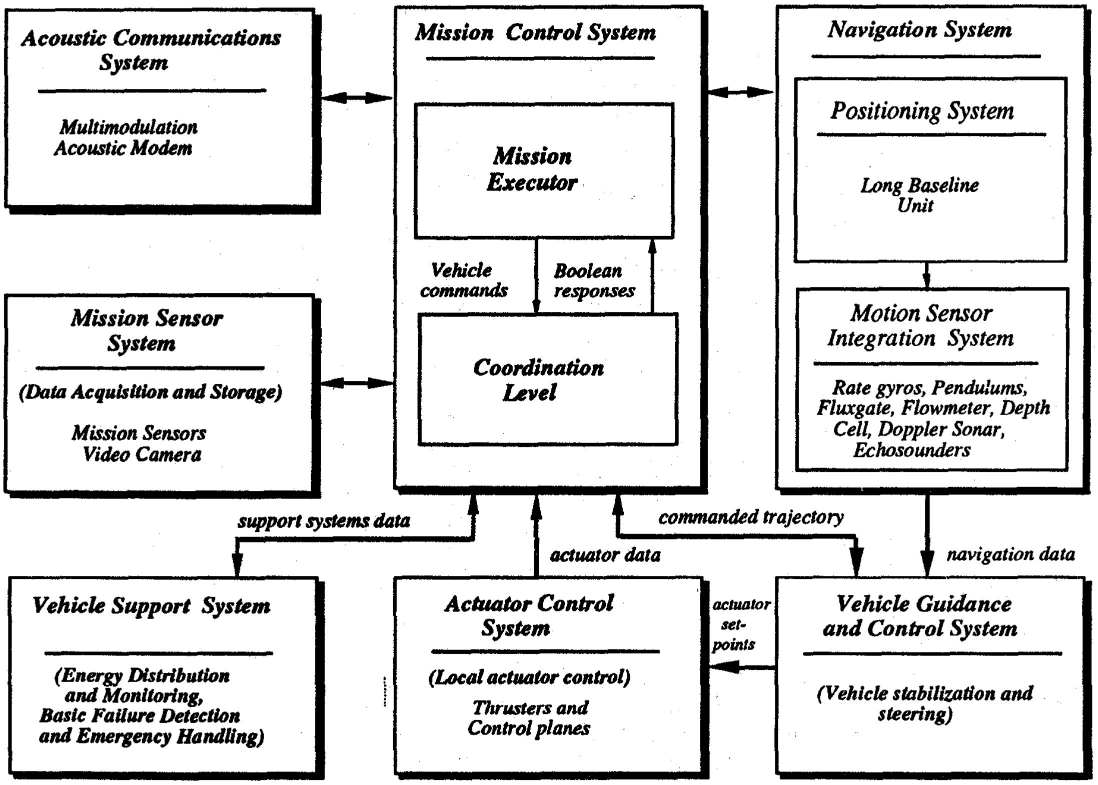

Figure 2 Functional Diagram for Mission and Motion Control