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MARIUS: An Autonomous Underwater Vehicle for Coastal Oceanography

An Autonomous Underwater Vehicle (AUV) named MARIUS has been developed under the MAST Programme of the Commission of the European Communities. The primary envisioned missions of the prototype AUV are environmental surveying and oceanographic data acquisition in coastal waters. The authors describe the design and implementation of the AUV systems for Vehicle and Mission Control, and report the results of the sea trials conducted with the vehicle in Sines, Portugal.

Keywords: Autonomous underwater vehicles, coastal oceanography, vehicle and mission control systems, mission management systems

The development of a prototype autonomous underwater vehicle (AUV) for environmental surveying and oceanographic data acquisition in coastal waters is described. The vehicle, named MARIUS, has been designed and built by a multidisciplinary team of scientists and engineers from Denmark, France, and Portugal, with support from the MAST (Marine Science and Technology) Programme of the Commission of the European Communities. The research and development work was initiated in 1991 in the scope of the MAST-I UBC project, leading to the design and testing of the basic vehicle systems for propulsion, communications, and vehicle control; see [15] and the references therein. That work continued under the MAST-II SOUV project, lasting from 1993 to 1995, that focused on the upgrading of the vehicle for operation at greater depths, and on the development, integration, and sea testing of advanced systems for Vehicle and Mission Control, as well as Mission Management [2,16].

This paper provides a survey of the research and development activities that were pursued in the scope of both projects. Due to space limitations, however, it focuses on the development and testing of the AUV systems for Vehicle and Mission Control that were developed under the MAST-II SOUV project. The paper is organized as follows. In the next section we present the main motivation for the development of MARIUS. An environmental mission scenario off the coast of Denmark is described, and its impact on the vehicle's performance requirements is briefly analyzed. The following section sets a general framework for the discussion to follow. A general description of the vehicle is provided, and its functional system organization is detailed. Special emphasis is placed on the

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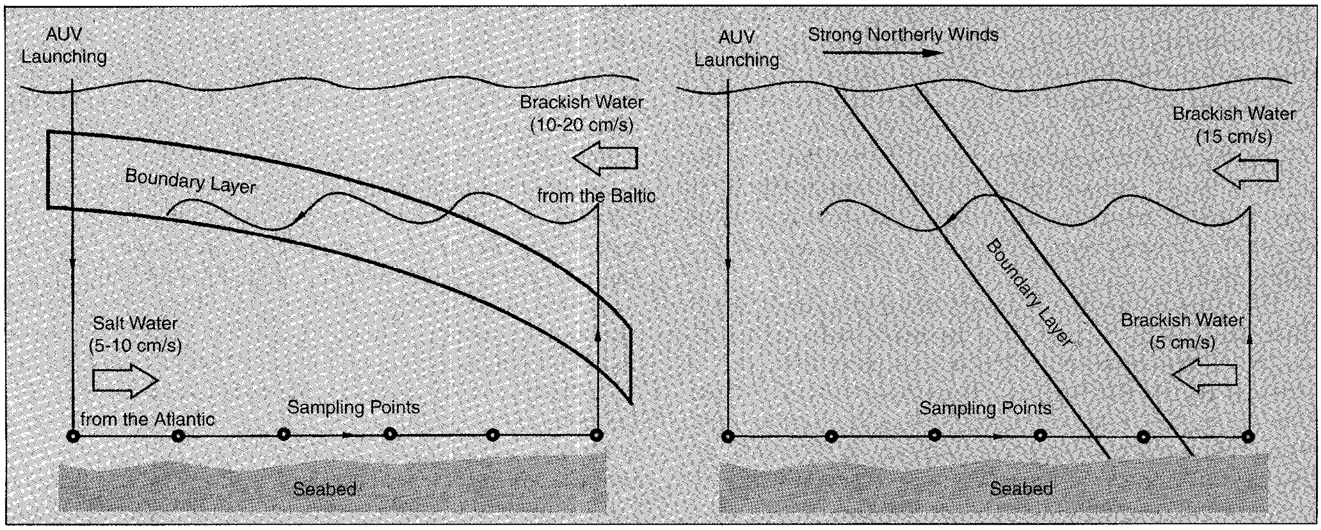

Figure 1. The Kattegat area—left: surface and bottom currents in opposite directions; right: surface and bottom currents in the same direction.

systems for navigation, guidance and control, as well as on those for vehicle support, environmental inspection, communications, and mission control. The computer network that was selected to implement the above systems is also described. Next we introduce the multimodulation acoustic communication system that was developed to communicate between the vehicle and a support ship, and describe the acoustic tests that were carried out in a pool and at sea. In addition, we summarize the progress made towards the development of an electrically scanned, multibeam sonar for obstacle detection purposes. The following section describes the theoretical framework that was adopted for the integrated design of the vehicle's navigation, guidance, and control systems to achieve precise maneuvering in the vertical and horizontal planes and accurate inertial reference trajectory tracking. This is followed by an introduction of the general Petri net based methodology that was selected for the design and development of the vehicle's Mission Control System. The system allows for easy programming of simple vehicle missions, and contains the basic kernel for the implementation of the more advanced vehicle Mission Management System. We then summarize the methodology adopted for the design of a Mission Management System for the vehicle that includes a Mission Preparation and a Mission Execution module. Finally, we describe the results of an intensive series of sea tests that were conducted with the vehicle in Sines, Portugal, with the objective of assessing the performance of the AUV systems for Vehicle and Mission Control.

MISSION SCENARIOS AND PERFORMANCE REQUIREMENTS

This section describes one envisioned mission scenario for the MARIUS AUV, off the coast of Denmark. For other mission scenarios in Atlantic waters, the reader is referred to [15,16,17]. The missions studied take place in coastal waters, and focus on civilian applications; furthermore, they address environmental problems that require non-traditional underwater surveying techniques. The envisioned missions were defined in the course of a multidisciplinary study that involved marine biologists and geologists. They served the dual purpose of: i) helping disseminate the concept that AUVs can play a major role in the future exploration, surveillance and rational exploitation of the ocean, and ii) setting realistic goals against which to compare the expected technical performance of the vehicle under development.

Mission in the North Sea/Skagerrak - Kattegat Area

COWIconsult and the Danish Environmental Research Institute (Danmarks Miljø Undersøgelser - DMU) have recently defined an interesting AUV mission scenario in the North Sea/Skagerrak-Kattegat region of Denmark. In this area, currents from the Baltic Sea and the North Sea/Atlantic Ocean meet and pelagic fronts are formed (see Figure 1). The water from the Atlantic is cooler, saltier, and richer in oxygen than that from the Baltic. The mixing process gives rise to a boundary layer region (frontal area) where the salinity and current vary gradually. Depending on the direction of the prevailing surface winds, the interaction between the two bodies of water produces different current patterns near the surface and close to the seabed. Under strong northerly winds, the boundary layer in the intermediate water column shifts, and shows a pronounced inclination, as depicted in Figure 1.

It is known that such frontal areas sustain high pelagic productivity (e.g., phytoplankton). A major part of this production is likely to be channeled to higher trophic levels. However, little is known of how much of the pelagic production ends up in the benthos (bottom-dwelling organisms). Earlier investigations using traditional methods have indicated elevated densities/biomasses of suspension feeding benthos in some parts of the area, possibly as a consequence of the increased concentration of phytoplankton. This is a subject of considerable importance, in view of its possible role in triggering the occurrence of large, desolated areas of the seabed depleted of oxygen.

The proposed benthic survey aims at localizing and estimating the spatial extension of areas with high sedimentation or lateral input of phytoplankton to the benthos, and establishing their correlation with the pelagic front area. These objectives can be achieved by quantifying suspension feeding bottom fauna using imaging techniques, measuring fluorescence and the concentration of oxygen, and taking phytoplankton samples from the water near the seabed for post-mission analysis. The extension of the frontal zone (50km×50km), the water depths (from 30 to150m), and the need to "probe" for interesting features underwater in an unsupervised manner, make traditional surveying using divers or towed sensors very costly or inadequate to the task at hand.

The mission envisioned consists of a grid survey along 11 linear tracks (with 10 to15 sampling points each), with a distance of 3600m between tracks. Each line is cruised twice, at different depths: this leads to a bottom survey in one direction, followed by a surface survey back to the starting point while performing an undulating maneuver to determine the spatial extension of the boundary layer. During the survey, the following programme must be carried out:

- Vehicle cruising between sampling points, at a constant speed (1m/s) and height (1-2m) above the seabed—the sensor payload will acquire data on temperature, salinity and fluorescence; one-minute video recordings of the seabed will be taken every five minutes if light conditions permit.
- Vehicle cruising at low speed or hovering over selected points along the line tracks—video recordings of 10 seconds; vertical photographs covering a seabed area of 50cmx50cm, with a resolution of 1mm; monitoring of fluorescence and oxygen 5cm above the seabed; taking of phytoplankton samples. Positioning accuracy at the sampling points: ±100m. Height accuracy while video recording: ±0.1m. The quality of the video recording and photographs will allow identifying organisms down to the size of 5cm, as well as estimating the gross amount of organisms as small as 1mm.
- Vehicle cruising below the sea surface (depth of 10-20 meters), on the way back to the starting point—acquisition of temperature, salinity, and fluorescence data while performing an undulating maneuver.

In the programme described, the vehicle is required to withstand currents with a maximum value of 1m/s and avoid unknown small obstacles on the seabed. It is important to remark that the mission proposed implies a survey distance on the order of 500km. This is well beyond the mission range achievable with the existing vehicle. The short term objective is to survey one line in one simplified mission. After changing the batteries, a new line can be scanned. The experience acquired will help determine if it is economically feasible to plan a fleet of AUVs to perform the original survey with multiple vehicles operating in cooperation.

In this and other envisioned mission scenarios [15], the vehicle is launched from a support ship after a mission plan has been downloaded to the vehicle's computer network. The mission plan includes a description of the trajectories to be followed, together with the tasks to be completed at selected inspection sites along the trajectories (e.g., collecting environmental data using dedicated sensors, or gathering images using a video camera). The vehicle determines its attitude and position underwater using an integrated navigation system, and computes commands to the thrusters and control surfaces so as to achieve precise trajectory following. During the mission, the vehicle may exchange information with a support ship via an acoustic link. This is a low data rate link with the sole objective of receiving new mission specifications and relaying data regarding the overall state of the vehicle (e.g., battery charge information and failure reports).

Guided by a detailed analysis of the missions envisioned, a basic set of performance requirements for the MARIUS AUV have been specified [16]. These include the following: i) meeting adequate tradeoffs between open-loop platform stability and closed-loop maneuverability, ii) achieving robustness against plant parameter variations, iii) reducing the impact of external disturbances (e.g. wave action) and sensor noise on the vehicle's performance, iv) recovering from a selected number of hardware failures, and v) having the possibility to program, run, and follow the execution of vehicle missions using user friendly interfaces. These considerations led to a baseline body configuration for the vehicle and to the basic vehicle system organization that are described next.

THE MARIUS AUV: SYSTEM ORGANIZATION

The MARIUS vehicle is shown in Figure 2. The vehicle is 4.5m long, 1.1m wide and 0.6m high. It is equipped with two main back thrusters for cruising, four tunnel thrusters for hovering, and rudders, bow, and stern planes for vehicle steering and diving. Attached to the top part of the hull are an acoustic link transducer and its respective baffler, and a transducer that is part of a long baseline positioning system. The vehicle has an approximate weight of 2200kg, a payload capacity of 50kg, and a maximum operating depth of 600m. Its maximum rated speed with respect to the water is 2.5m/s. At the speed of 1.26m/s, its expected mission duration and mission range are 18.4h and 83km, respectively. The interested reader is referred to [5,16] and the references therein for details of the mechanical construction of the vehicle by COWIconsult/MARIDAN.

Vehicle System Organization

This section contains a brief description of the basic vehicle systems and their interconnections (vehicle functional orga-

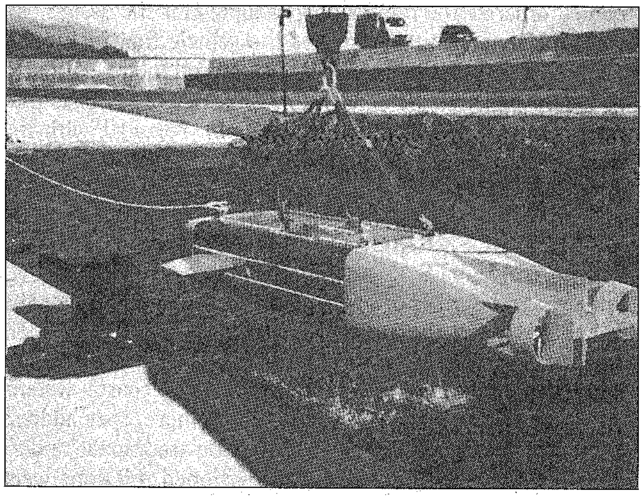

Figure 2. The MARIUS vehicle.

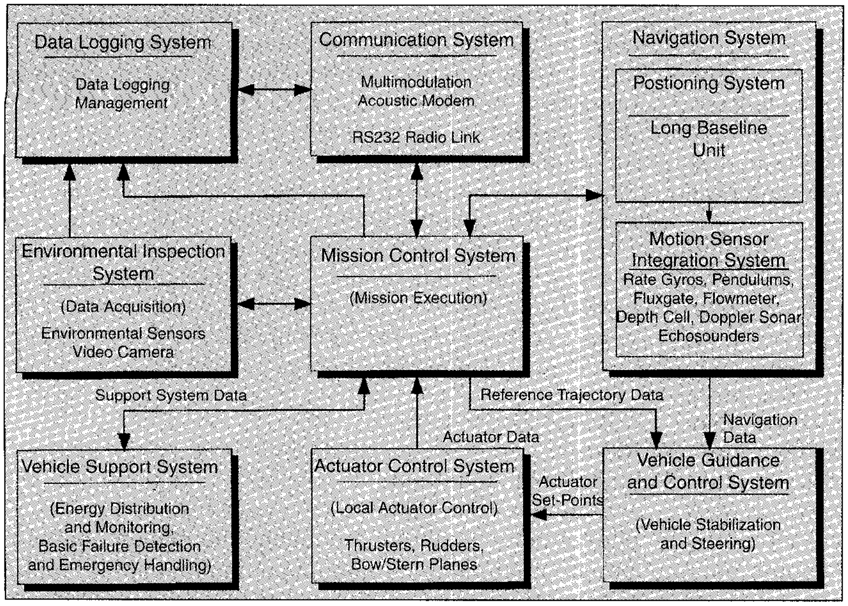

Figure 3. Vehicle System Organization.

nization). The software architecture that is used to implement those systems, as well the supporting computer hardware, actuators, and sensors, are described elsewhere [5,16]. The following basic systems can be identified in Figure 3:

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 subsystems and, during operation, of detecting basic hardware failures and triggering emergency reflexive maneuvers whenever required (e.g., upon detection of a leak in a pressure container, it forces the vehicle to 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 rudders, bow, and stern planes. Actuator set points are provided by the Vehicle Guidance and Control System. Actuator data are fed back to the Mission Control System for vehicle status assessment.

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 the Positioning System (a long baseline unit with a network of transponders) and a Motion Sensor Integration System. The motion sensor package includes the following units: i) 3 *rate gyros*, 2 *pendulums*, and 1 *magnetometer* (Watson Attitude & Heading Reference Unit AHRS-C303), ii) 1 *flowmeter* TSA-06-C-A (EG & G Flow Tech.), iii) 1 *depth cell* DC 10R-C (Transinstruments), iv) 2 *echosounders* ST200 operating at 200 KHz (Tritech), and v) 1 *Doppler Log* TSM 5740 with 4 beams in a Janus configuration, operating at 300 KHz (Thomson-ASM).

The outputs of the Navigation System are fed back to the Vehicle Guidance and Control System, and sent to the Mission Control System for vehicle performance assessment.

Vehicle Guidance and Control System (*VGCS*)—The Vehicle Guidance and Control System accepts as inputs reference trajectories issued by the Mission Control System, 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 surfaces), so that the vehicle will achieve precise trajectory tracking in the presence of shifting sea currents and vehicle parameter uncertainty. In applications where precise trajectory tracking is not required, the module in charge of the vehicle's guidance is responsible for achieving accurate tracking of set-points that include the vehicle's desired speed, depth, and heading.

Communication System (*COMS*)—The Communication System controls a bidirectional link that is used by the operator to issue mission directives to the Mission Control System, and by the vehicle to relay back information regarding its internal state and/or the state of progress of the mission. Two distinct modes of operation are possible: i) via an RS232 radio link, when the vehicle is at the surface, or submerged but pulling a small buoy with an antenna, and ii) via an acoustic modem, otherwise. The bidirectional acoustic link of MARIUS enables real-time communications with a support ship in shallow water, up to a distance of 3km, at a frequency of 12KHz [1,3].

Typically, short messages are sent across the acoustic channel such as on-line mission commands, user requests for data, and sensor readings. For operation in shallow waters, the main difficulty facing this system is to achieve communications at long distance in the face of multipath propagation.

Environmental Inspection System (*EIS*)—The Environmental Inspection System collects data from a suite of environmental sensors that measure conductivity, temperature, pressure, turbidity, fluorescence, oxygen, and pH. A video camera is included to provide close-up images of the seabed. Data acquisition is controlled by the Mission Control System.

Data Logging System (*DLS*)—The Data Logging System acquires and stores internal vehicle data. The data stored can be used for on-line consistency analysis, and for post-mission processing.

Mission Control System (*MCS*)—The Mission Control System is the basic kernel of a complete system for Mission Management (i.e., Mission Preparation and Mission Execution) that has been designed for the MARIUS vehicle; see [16,18] and the references therein. Based on a Mission Program obtained from a set of mission specifications, the Mission Control System sequences and synchronizes the execution of the basic vehicle system tasks that concur to the execution of that mission, and provides inbuilt recovery to vehicle and mission level faults. At the present stage of development, the Mission Control System is being implemented on the computers resident on board the vehicle as a set of configurable Petri Nets that control the flow of commands and data among the vehicle systems; see [14,16].

Vehicle Computers

To implement the systems described, the MARIUS AUV is equipped with an open, distributed hardware/software architecture that simplifies the tasks of incrementally adding sensor and actuator interfaces, as well as processing power. The reader will find in [16] complete details on the vehicle computer network and the corresponding software organization; see also Figure 4.

Currently, the MARIUS computer network includes two MC68020+FPU (microprocessor and floating point) based computers, and a more advanced MC68030+FPU computer. The first two units, named the *Navigation Computer* and the *Control/Support System Computer*, implement Navigation, Guidance, Control, and Vehicle Support System management tasks. The third unit implements the vehicle's Mission Control System. The *Positioning System Computer* (*PSC*) supervises the operation of a long baseline unit that is part of the vehicle Navigation System. The *Acoustic Communications Computer* (*ACC*) is at the core of a half duplex acoustic modem for acoustic transmission between the vehicle and a surface unit. The Positioning System Computer and the Acoustic Communications Computer are stand-alone units. In this application, they are simply viewed as peripherals of the Navigation Computer, Control/Support System Computer, and Main Computer, which consist of Gespac and MPL boards connected to standard G96 buses. The MC680X0 based computers run the OS-9 operating system, which allows for real-time multi-tasking operation, process and memory management, and interprocess communication facilities that include shared memory and events. The vehicle's Local Area Network (LAN) has been designed to allow easy upgrading from the current *RS*232/ 19.2 Kbaud point to point communication network to an industrial standard CAN Bus.

ACOUSTIC SYSTEMS: COMMUNICATION EQUIPMENT AND SONAR

This section describes the acoustic communication link of the MARIUS AUV, and summarizes the progress achieved in the development of an electrically scanned sonar for obstacle detection.

Acoustic Communications

At the heart of the acoustic communication link of the MARIUS AUV is a digital multi-modulation transmission system (developed by ORCA Instrumentation) whose modulation schemes and baud rates can be remotely configured during operation. A simple, phase-coherent modulation scheme enables high-rate communications in the vertical channel, that is, when the emitter and receiver are located approximately along the same vertical line, at different depths. Spread spectrum techniques are used for reliable low-rate communications in the horizontal channel.

In a typical mission scenario, an operator installed on board a ship initializes the communication system by signaling the underwater unit to transmit a test message. He then evaluates in real time the quality of the reception, and chooses the modulation scheme and baud rate that are better suited to the tasks being performed. This procedure can be repeated throughout the mission. Short, high-level mission definition commands are transmitted from the ship to the vehicle. Data from the vehicle to the support ship include selected sensor readings, malfunction warnings, and updates on the state of progress of the mission. The reader is referred to [1,3] and the references therein for information regarding the equipment developed and the results of pool and sea trials.

Acoustic System Implementation

Three types of modulation schemes are currently supported by the communications equipment: i) *Phase Shift Keying* (*PSK*)—an easy to implement, bandwidth efficient, classical phase-coherent modulation, ii) *CHIRP modulation* —a linear frequency modulation scheme that is commonly used in radar and sonar for target detection, and iii) *Frequency Hopping*—a frequency modulation technique that combines some of the characteristics of CHIRP and PSK by coding the data symbols as linear frequency excursions.

The spread in frequency that results from the use of CHIRP and Frequency Hopping modulations allows to combat multipath effects much more effectively than using simple PSK techniques. Therefore, the last two modulation schemes

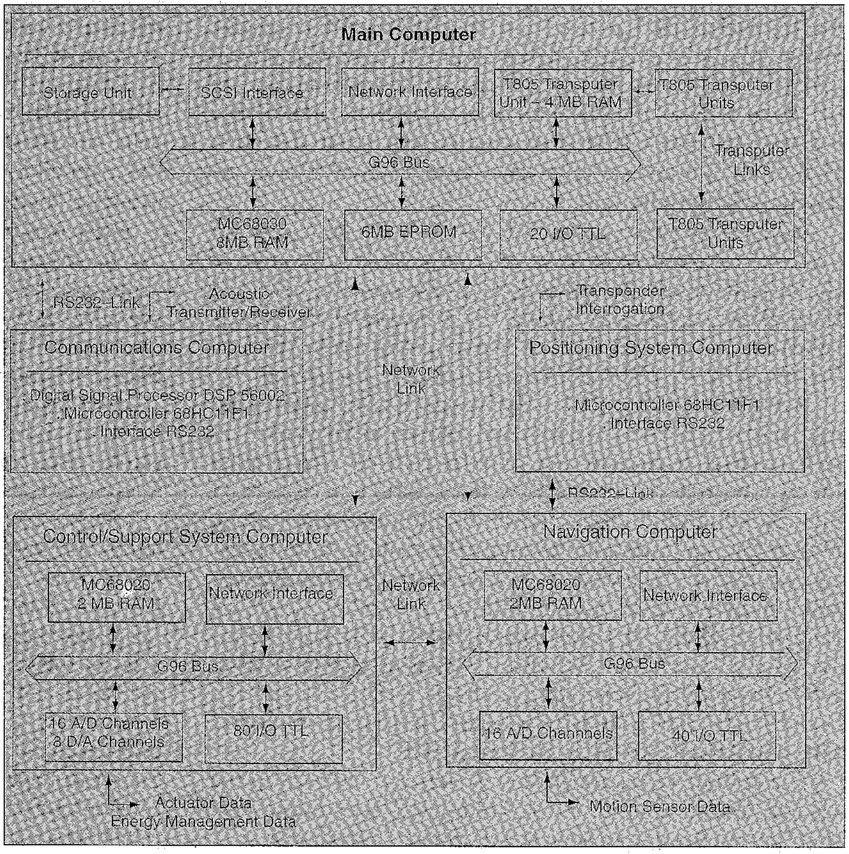

Figure 4. Vehicle Computer System.

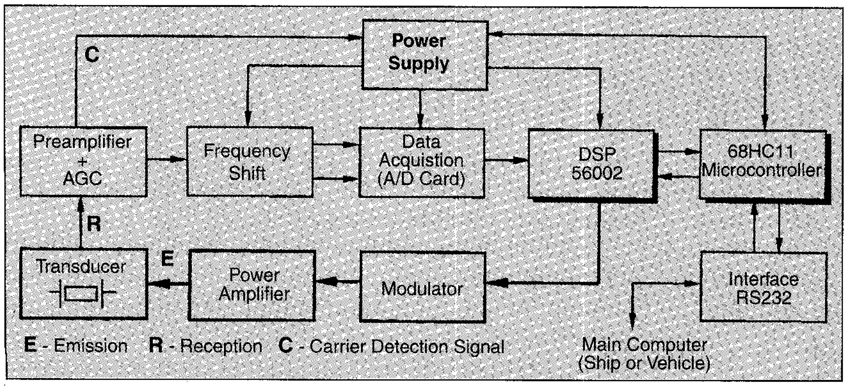

Figure 5. Multimodulation communication system - hardware implementation.

are specially suited for communications in the horizontal channel, where extensive multipath fluctuation, and thus severe intersymbol interference may occur. As a tradeoff, there is a decrease in the maximum data transmission rate achievable as the complexity of the modulation scheme increases from PSK to Frequency Hopping, and to Chirp.

Figure 5 is a block diagram of the basic hardware that implements each unit of the multimodulation acoustic transmission system. The surface and underwater units consist of three cards each, built around two low power consumption microcontrollers and a Motorola DSP56002 running at 40Mhz:

- a preamplifier card consisting of a constant gain amplifier, an automatic gain control (AGC) system, and a low power microcontroller
- a power amplifier and a transducer matching stage
- a mother board that powers up the other two boards, implements the modulation and demodulation schemes, and controls the flow of data through an *RS232C* interface.

In the idle mode, only the preamplifier stage is powered to detect incoming signals. If a call is detected, the power supply of the main board is switched on and the incoming signals are processed. Each unit can also be awaken to transmit data via the RS232C interface. The acoustic modem developed has the following characteristics: i) Frequency: 10-14KHz and 50-58KHz, ii) Baud rate: CHIRP:20bit/s, Frequency Hopping: 100 and 200bit/s, PSK: 300, 600, 1200, and 2400bit/s, iii) Acoustic Power: 180dB ref. 1μPa at 1m for an omnidirectional transducer (standard), iv) Receiver Sensitivity: 100μV with S/N app. 0dB, v) Dimensions: Length - 620mm, Diameter - 140mm, and vi) Weight:15Kg in air.

Acoustic Pool and Sea Tests

The French Ocean Agency IFREMER has played a major role in the tests of the Acoustic Communication System. The first trials were performed at the test pool of IFREMER, Centre de Brest, France. The objective of the trials was to test the performance of the signal processing algorithms in the presence of multipath effects caused by successive reflections of the acoustic waves on the walls, surface, and floor of the pool. Later, several campaigns at sea, on board the *Sainte Anne* and *R/V Thalia* ships owned by IFREMER, were conducted during the period from March 1992 to March 1995.

Communications between a line moored, self-contained unit placed at approximately 5m above the seabed and a drifting ship were tested at different water depths (20-100m). During the first trials at sea, no message coding was performed. At the Bay of Brest, no errors were detected in messages 5000 bit long transmitted over distances of 200 to 4000m, using a frequency range of 10-14KHz and CHIRP modulation at 20bit/s. On other locations, using the same modulation scheme and data rate, the error rate never exceeded 10^{-03}. Experiments in the 50-58KHz band at 100 and 200bit/s using Frequency Hopping modulation exhibited higher error rates, up to 10^{-02}. Later experiments using VITERBI encoding and decoding brought down the error rate in all cases to under 10^{-05}.

The modem described has been designed for a performance upgrade, so that adaptive equalization algorithms could be implemented without substantial modifications in the hardware. This is a subject of great interest in the development of future digital acoustic modems, which should be able to perform reliably in the presence of multipath propagation, rapidly changing channel characteristics and Doppler shift. Encouraging results in this area are reported in [3,16], where the authors describe the design, implementation and preliminary testing of an underwater communications system that builds on adaptive equalization techniques using the equipment described above.

Sonar

The main objective of the research and development work carried out by RESON A/S under this project was twofold: i) to upgrade an electrically scanned sonar system named "SeaBat 6012" in order to accommodate a 3 beam controllable projector and the associated transmitter electronics, and ii) to develop algorithms for real-time obstacle detection. The resulting sonar system should be instrumental in providing AUVs with the characteristics of the MARIUS with the capability of detecting and avoiding unforeseen obstacles along their course [10]. The complexity of the system at hand precluded a complete integration of the sonar unit with the remaining systems in the AUV. However, the following important milestones were achieved (see [16] for details):

Design of a 3 beam steerable projector and transmitter electronics—the transmitter transducer technical requirements were specified, and the corresponding hardware was designed. The specifications include the following: Horizontal coverage: 120°; Uniform ±3dB coverage: 90°; Vertical coverage: ±7 to 10°; Vertical beams: 3 beam planes; Vertical opening angle: 5 to 7°; Vertical sidelobes: at least <20dB; Acoustic power output: 200W, 1 percent duty; Depth rating: 600m; Maximum vertical individual elements: 16; Impedance: 100 to 1000ohm per element; Centre frequency: 455KHz.

Development of Computer Hardware and Software for Obstacle Detection—an interface between the SeaBat 6012 sonar and an image processing computer was developed by introducing a current buffer on some of the signals that are internal to the SeaBat processor. These signals were then connected to an ISA-bus interface hosted by a PC that enabled recording, storing, and manipulating the echo signals obtained. The system was used to record real sonar data during an ROV mission that was carried out in cooperation with the Danish Navy and the Servolaboratoriet of the Technical University of Denmark. The data recorded were used for testing different signal processing algorithms. The system has gone through different upgradings, and brought to the level where an interface between the SeaBat 6012 and an 68040 based VME board has been developed. The basic algorithms for data filtering, image detection, and object analysis have been completed and tested in the laboratory; the corresponding reports are included in [16].

NAVIGATION, GUIDANCE, AND CONTROL SYSTEMS

The development of reliable navigation, guidance, and control systems for AUVs poses great challenges to system engineers, both from a theoretical and practical standpoint. To meet those challenges, the undersea robotics group of IST has initiated, in the course of the MARIUS development project, a long term research programme that aims at developing a theoretical framework for the integrated design of guidance, navigation and control systems for Autonomous Underwater Vehicles. See [13] for a comprehensive presentation of those systems, which are depicted in Figure 6: i) *Navigation*, to provide estimates of linear and angular positions and velocities of the vehicle, ii) *Guidance*, to process navigation/inertial reference trajectory data and output set-points for the desired vehicle's (body) velocity and attitude, and iii) *Control*, to generate the actuator signals that are required to drive the actual velocity and attitude of the vehicle to the values commanded by the guidance scheme. The main practical objective of the programme in course is to develop vehicle controllers that can achieve accurate *trajectory tracking* or *path following* during survey missions.

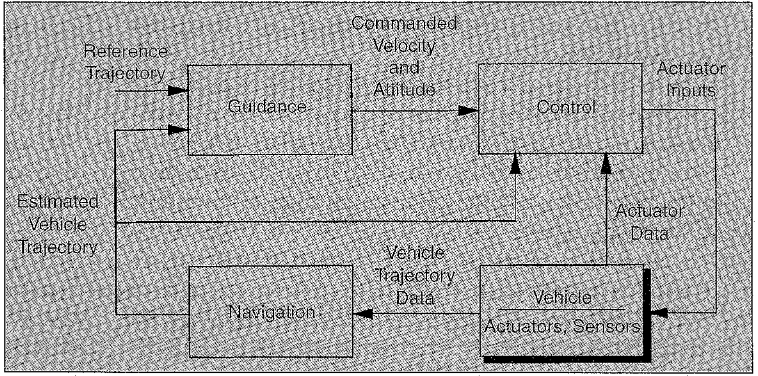

Figure 6. Navigation, Guidance and Control.

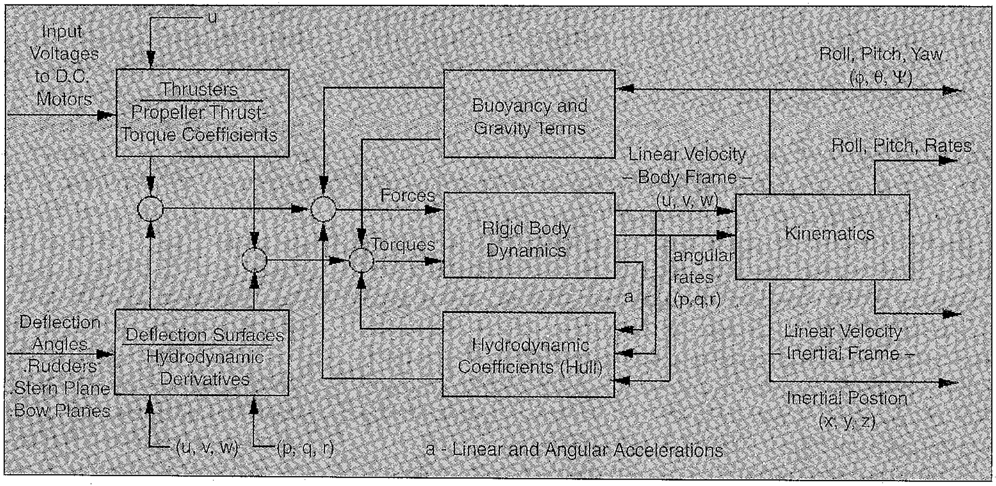

Figure 7. Vehicle Model.

The basic theoretical framework adopted is explained in [7] with a design exercise in which recent developments in H-Infinity (H_∞) control theory, multi-rate navigation techniques, and the classical line of sight (LOS) guidance strategy were applied to the design of a trajectory tracking controller for the MARIUS AUV. The key ideas in the design methodology adopted are to clearly state all performance specifications in the frequency domain, and to use design tools that can handle those types of specifications. Thus, the natural constraint that the navigation, control, and navigation systems exhibit different bandwidths, can be incorporated directly in the system design phase. Analysis of the integrated system is performed using a simulation package named INTEGRA [16], developed at IST, that allows studying the impact of the navigation, guidance, and control algorithms on the overall vehicle performance. For an introduction to these important subjects, the reader is referred to [7], which describes the natural sequence of basic steps adopted in the design of the navigation, guidance, and control algorithms for MARIUS. A brief summary of the methodology adopted is described below.

Vehicle Modeling and Identification. The general structure of the vehicle model is depicted in Figure 7. The model is standard, and was simply derived from basic principles of physics that borrow from the theory of rigid body dynamics and kinematics, as well as hydrodynamics. System identification, however, was far more complex and required the combination of theoretical and experimental methods to determine the most important hydrodynamic coefficients of the vehicle and the thruster characteristics. The results of the hydrodynamic tank tests conducted at the Danish Maritime Institute in Lyngby, Denmark with the full scale prototype vehicle, are reported in [5]. The complete estimated model can be found in [22].

Gain Scheduled Control System Design. The methodology adopted for nonlinear control system design method was gain-scheduled control theory. Using this approach, the design of a controller to achieve stabilization and adequate performance of a given nonlinear plant (system to be controlled) involves the following sequence of steps:

i) *Linearizing* the plant about a finite number of representative operating points.

ii) Designing *linear controllers* for the plant linearizations at each operating point. The methodology selected for *linear control system* design was H_∞ control. This method rests on a firm theoretical basis, and leads naturally to an interpretation of control design specifications in the frequency domain. Furthermore, it provides clear guidelines for the design of controllers to achieve robust performance in the presence of plant uncertainty.

iii) *Interpolating* the parameters of the linear controllers of Step ii) to achieve adequate performance of the linearized closed-loop systems at all points where the plant is expected to operate. The interpolation is performed according to an external scheduling vector (e.g., dynamic pressure), and the resulting family of linear controllers is referred to as *gain scheduled controller*.

iv) Implementing the nonlinear gain scheduled controller on the original nonlinear plant, using a new methodology introduced in [11].

A design example that illustrates the application of this circle of ideas to the development and sea testing of a control system for the MARIUS vehicle in the vertical and horizontal planes, can be found in [22].

Multi-Rate Navigation System Design. The objective of the AUV Navigation System is to obtain accurate estimates of the position and attitude of the vehicle and respective rates, based on measurements available from the motion sensor suite installed on-board the vehicle we described earlier. The estimates are input to the Vehicle Guidance and Control systems.

In [7,8], the problem of designing a navigation system for the MARIUS AUV was essentially decoupled into two problems: i) estimation of attitude and attitude rate, and ii) estimation of linear position and velocity. Whereas the first problems leads naturally to single-rate filters, the latter requires dealing with time-varying or multi-rate filtering. This stems from the fact that due to the characteristics of the acoustic channel, the measurements from the Positioning System (Long Baseline unit with an array of transponders) may be available at a rate that is much smaller than that of the remaining sensors (flowmeter and Doppler Log). This problem has been addressed and solved by exploring the relationship between multi-rate and periodic systems, and using some algebraic and analytical results on the equivalence between discrete-time periodic and time-invariant systems. The reader will find in [8,16] complete details on the design of a complementary, discrete-time, multi-rate filter for the vehicle based on information available from the Long Baseline system and the Doppler sonar. Interestingly enough, the setup adopted for multi-rate filtering allows for a frequency like interpretation of the resulting time-varying operators. According to that interpretation, the resulting filter will complement the information obtained from the Long Baseline system at low frequency, with that obtained from the Doppler log at high frequency.

Guidance, Integrated Simulation with Navigation and Control. The purpose of the Guidance System is to generate the references that are applied to the AUV control system, in order to achieve accurate trajectory tracking or path following. Conceptually, the design of a classical guidance system is simple, as it relies solely on the kinematics equations of the vehicle. The basic strategy involved is easily explained in the case of path following by restricting the motion of the vehicle to the horizontal plane, and assuming that the vehicle progresses at constant forward speed, with a small sideslip angle. In this case the role of the guidance gystem is reduced to computing the reference command for yaw angle, so that the main axis of the vehicle will point to a conveniently defined imaginary point located on the reference trajectory (line-of-sight strategy). The application of this guidance law to the MARIUS AUV is summarized in [7]. It is well known that this simple approach to path following is not suited for the case where the vehicle dynamics are slow, and may in fact lead to instability. To cope with those issues, the general framework for guidance and control systems design has been extended in [8] and [21] to the problems of trajectory tracking and path following, respectively, leading to a methodology whereby guidance and control are effectively designed at the same time. This represents a clear departure from classical approaches in that the constraints of the vehicle dynamics are directly incorporated in the design of a trajectory tracking or path following controller.

MISSION CONTROL SYSTEM

Among the challenges that face the designers of underwater vehicle systems, the following is of the utmost importance: design a computer based Mission Control System that will:

- enable an operator to define a vehicle mission in a high level language, and translate it into a mission plan,
- provide adequate tools to convert a mission plan into a Mission Program that can be formally verified and executed in real-time,
- endow an operator with the capability to follow the state of progress of the Mission Program as it is executed, and modify it if required.

Meeting those objectives poses a formidable task to underwater system designers, who strive to develop vehicles that can be programmed and operated by end-users that are not necessarily familiarized with the most intricate details of underwater system technology. Identical problems face the designers of complex robotic systems in a number of areas that include advanced manipulators, industrial work cells, and autonomous air and land vehicles. The widespread interest of the scientific community in the design of Mission Control Systems for advanced robots is by now patent in a sizable body of literature that covers a wide spectrum of research topics focusing on the interplay between event driven and time-driven dynamical systems. The former are within the realm of Discrete Event System Theory [4], whereas the latter can be tackled using well established theoretical tools from the field of Continuous and Discrete-Time Dynamical Systems.

Early references in this vast area include the pioneering work of Saridis [20], which set the ground for the study of learning control systems and intelligent machine organization. For an overview of recent theoretical and applied work in the field, the reader is referred to [9,12,19,23,24], that contain a number of interesting papers on the design of advanced Mission Control Systems for intervention robots, underwater vehicles, and unmanned aircraft.

Spawned from the availability of small embedded processors and the ever increasing capabilities of underwater communications and acoustic sensors, there is now considerable interest in validating the theoretical approaches to Mission Control System design with experiments conducted with prototype vehicles.

References [12,19,24,25] contain a large number of publications describing vehicles operated by a number of universities and research institutes in Europe, Asia, and the US, and on the state of development of their Mission Control Systems. Representative vehicles include the VORTEX (IFREMER, France), ROBY (Istituto Automazione Navale, Italy), MARIUS (operated by the Instituto Superior Tecnico of Portugal on behalf of the European Commission), PHOENIX (Naval Postgraduate School, U.S.A.), ODYSSEY (M.I.T. Sea Grant Programme, U.S.A.), OCEAN EXPLORER (Florida Atlantic University, U.S.A.), OTTER (MBARI/Stanford, U.S.A.), MT-88 and TUNNEL SEA LION (IMTP, Russia), and PTEROA (Japan). The reader will find in [12,19,24] interesting discussions aiming at establishing a common syntax and framework for cooperation among the researchers in this challenging field, as well as identifying different issues/paradigms that warrant further investigation in the area of software and hardware architectures for underwater robotics.

As part of the international effort to develop advanced systems for underwater vehicle mission control, a first version of a Mission Control System for the MARIUS AUV has been developed and tested at sea. References [14,16] contain a description of the framework adopted for the design, analysis, and implementation of the Mission Control System proposed, and the results of a series of sea trials for system validation conducted in Sines, Portugal. The Mission Control System of MARIUS arose out of an intensive cooperation effort among IST and THOMSON-ASM, and was strongly influenced by the solid body of research carried out by INRIA/IFREMER in France, with applications to the VORTEX vehicle, and at NPS in the U.S. with applications to the PHOENIX vehicle; see [6,9,12] and the references therein.

The methodology adopted for the design of a Mission Control System for the MARIUS AUV builds on the key concept of *Vehicle Primitive*, which is a parameterized specification of an elementary operation performed by the underwater vehicle (e.g., keeping a constant vehicle speed, maintaining a desired heading, holding a fixed altitude over the seabed, or taking video images of the seabed at pre-assigned time instants).

Vehicle Primitives are obtained by coordinating the execution of a number of concurrent (*Vehicle*) *System Tasks*, which are parameterized specifications of classes of algorithms or procedures that implement basic functionalities in an underwater robotic system (for example, the Vehicle Primitive in charge of maintaining a desired heading will require the concerted action of the System Tasks in charge of motion sensor data acquisition, navigation, vehicle control algorithm implementation, and actuator control. Vehicle Primitives can in turn be logically and temporally chained to form *Mission Procedures*, aimed at specifying parameterized robot actions at desired abstraction levels. For example, it is possible to recruit the concerted action of a set of *Vehicle Primitives* to obtain a *parameterized Mission Procedure* that will instruct the vehicle to follow a *horizontal path* at constant speed, depth, and heading for a requested period of time. Mission Procedures allow for modular *Mission Program* generation, and simplify the task of defining new mission plans by modifying/expanding existing ones.

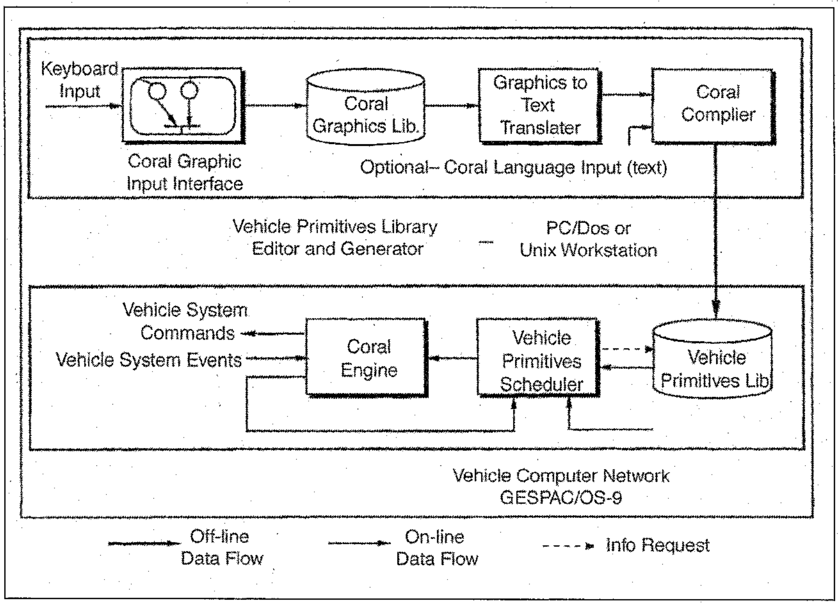

Figure 8. Mission Control System—basic organization.

Following the methodology developed in [14], System Task design is carried out using well established tools from continuous/discrete-time dynamic system theory, and finite state automata to describe its logical interaction with the Vehicle Primitives. The design and analysis of Vehicle Primitives and Mission Procedures build on the theory of Petri nets [4]. These are naturally oriented towards the modeling and analysis of asynchronous, discrete event systems with concurrency, where the transitions between events are enabled according to arbitrarily complex rules. This approach leads naturally to a unifying framework for the analysis of the logical behaviour of the discrete-event systems that occur at all levels of the Mission Control System. Vehicle Primitives and Mission Procedures can be developed and implemented using the specially developed software programming environments CORAL and ATOL, respectively. The first is a set of software tools that allows for graphically building a library of Vehicle Primitives embodied in Petri nets, and running them in real-time. The latter provides similar tools for Mission Procedure programming, but relies on a reactive synchronous programming language as a way to manage the potential complexity introduced by the occurrence of large Petri net structures. Whereas the first has been fully implemented, the latter has been specified

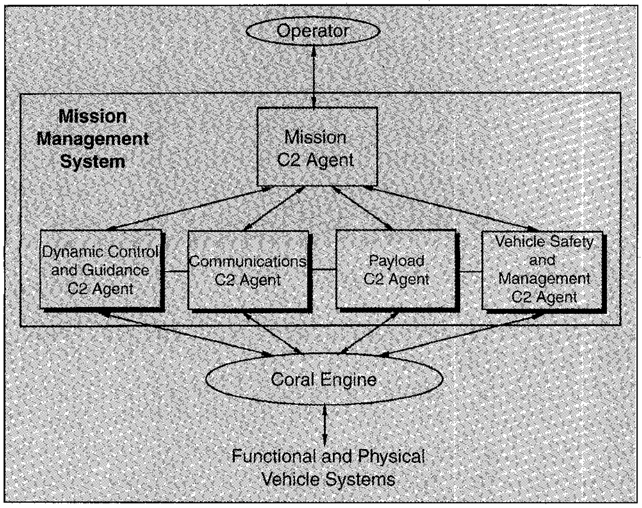

Figure 9. Multiple Agent Onboard MMS Architecture.

but is still under development.

At the core of the Mission Control System implementation is the CORAL software programming environment, which consists of two fundamental modules: i) the *Vehicle Primitives Library Editor and Generator*, and ii) the *CORAL Engine*; see Figure 8. The main goal of the Library Editor and Generator is to embody each Vehicle Primitive into a Petri net description, and to assemble a set of translated Vehicle Primitives into a Vehicle Primitive Library. The definition of each Primitive can be input either graphically through a CORAL graphic input interface, or directly using the CORAL language. A CORAL compiler/linker is in charge of processing the Vehicle Primitives inputs and of assembling the corresponding output data in the Vehicle Primitives Library. As an intermediate step, the CORAL graphic input interface produces a CORAL Graphics Library for later use during real-time operation. Currently, the Vehicle Primitives Library Editor and Generator can be run on a PC/DOS or on a Unix Workstation. During real-time operation, each Vehicle Primitive is executed by the CORAL Engine that sends commands to and receives responses from the Vehicle System Tasks that implement some of the functional blocks of Figure 3. Both the CORAL Engine and the software that implements the System Tasks run on the GESPAC OS-9 based target computer network of the MARIUS AUV. It is important to remark that the CORAL Engine remains fixed, and that the implementation of a new Vehicle Primitive simply requires that a new data set produced by the CORAL compiler be added to the Vehicle Primitives Library. This fact is important, as it simplifies the programming of new missions and makes the task of loading and unloading different Vehicle Primitives trivial.

The CORAL software environment was initially developed to implement Vehicle Primitives, only. However, it was realized early on that CORAL could also be used to implement a first kernel of a complete Mission Control System for the AUV, while the ATOL software programming environment was being developed. This was in fact done in the course of the MARIUS AUV project, leading to a methodology whereby Mission Programs and Mission Procedures are effectively embodied into—higher level—Petri Net descriptions that control the scheduling of Vehicle Primitives concurring to the execution of a particular mission. Furthermore, Mission Procedures and Mission Programs are generated using the graphic approach described above. During real-time operation, the Mission Control System can report its state to a Mission Assessment System implemented on a PC/DOS machine (using an aerial link during surface testing, or the acoustic communication link while diving). The information transmitted is then displayed on a computer screen using the CORAL Graphics Library described before. The state of progress of the mission can thus be evaluated by examining the evolution of tokens in selected Petri Nets. The set-up developed simplifies the steps that are necessary to go from concept to practice, effectively providing all the software tools that are required to automatically generate target that is run on the vehicle computer network. Furthermore, it provides simple graphic interfaces for mission programming, debugging, and mission follow-up.

The programming and execution of more ambitious missions requires the availability of more sophisticated off-line mission preparation tools, as well as capabilities for on-line mission assessment and mission organization. In the next section we will show how these requirements dictate the development of a true Mission Management System that can interface with the Mission Control System developed.

MISSION MANAGEMENT SYSTEM

This section contains a brief description of the Mission Management System (MMS) that was developed by THOMSON-ASM. Due to space limitations, only the MMS structure devoted to Mission Execution is summarized here. For an introduction to some background material and to the design phase of the complete system, see [16,18], which contain a very thorough description of so called Mission Execution and External Command Systems. The latter includes the systems for Mission Preparation, Mission Follow-up, and Post-Mission Analysis.

The MMS of MARIUS was designed to interact with the CORAL Engine of the previous section, while performing the following high level functions: i) interpreting mission plans (identifying goals and constraints imposed by mission specifications and vehicle safety requirements, respectively); ii) assessing permanently the state of progress of the mission and the environment, as well as the vehicle internal status; iii) deciding, based on the two previous capabilities, the "best" actions/reconfigurations to undertake in order to satisfy global mission goals, while maintaining the vehicle integrity (on-line mission organization); iv) triggering reflexive actions via rules dictated by an underlying mission doctrine, based on the foreseen impact of particular events, malfunctions, and failures.

The basic architecture adopted for Mission Management System design is depicted in Figure 9. The multi agent architecture consists of five C2 (Command and Control) agents [18] that perform the following functions: i) the Mission C2 agent is in charge of defining a detailed global plan to be executed, splitting the plan and sending its components to the corresponding four subordinate agents, and coordinating the decisions and actions of those agents; ii) each of the four Assistant C2 agents is in charge of a specific set of basic domains: dynamic control and guidance (motion control), communica-

Figure 10. MARIUS during a diving maneuver-Tests in Sines, Portugal.

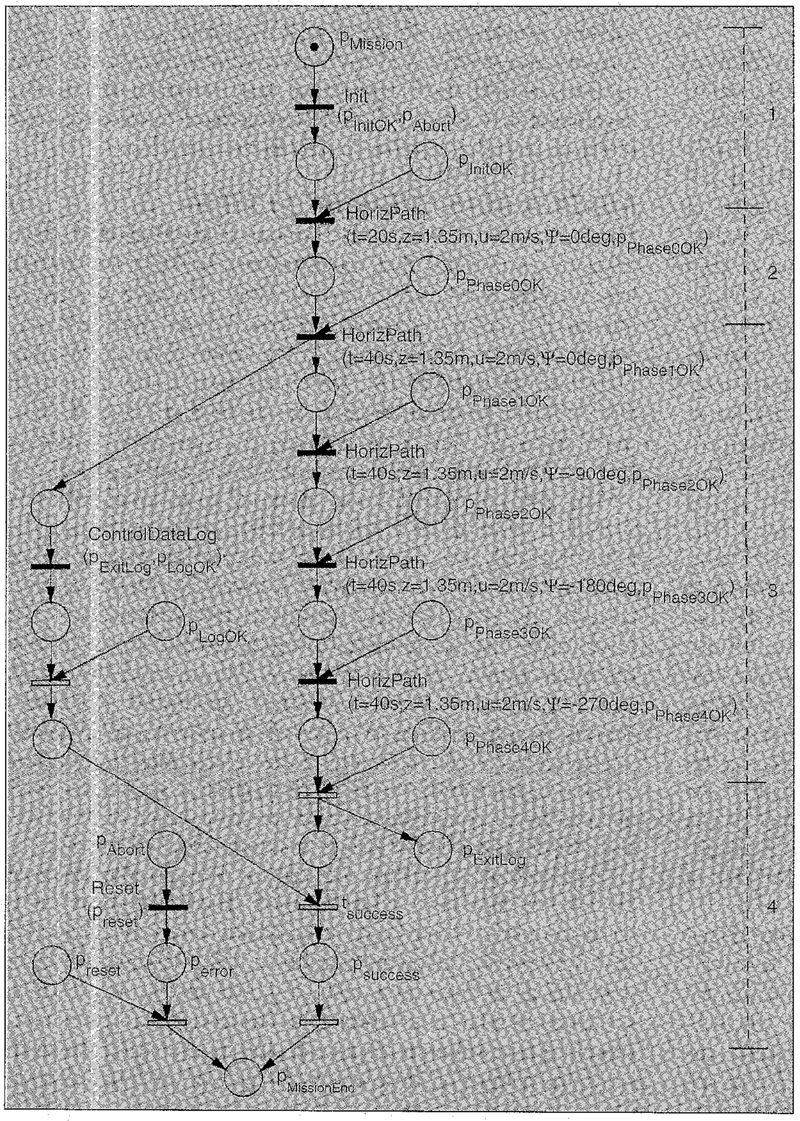

Figure 11. Mission program described in CORAL.

tions, mission payload, and vehicle safety management.

The architecture proposed has been fully specified from a functional point of view, and the software required for its implementation has been specified and designed. A first version of the MMS has been developed, and its performance assessed in simulation using a Unix Workstation [16]. Furthermore, laboratory tests have confirmed that the software architecture adopted for MARIUS is powerful enough to enable the complete integration between the MMS and the CORAL Engine described earlier here.

VEHICLE AND MISSION CONTROL OF MARIUS: TESTS AT SEA

Field tests of the MARIUS AUV were first carried out in Copenhagen Harbour in November 1993, and at sea in Denmark, in June 1994. The main objectives of those tests were to integrate the Vehicle Support and Actuator Control Systems, and to assess the maneuverability of the vehicle. The AUV was later transported to Portugal, where further system integration and sea tests of the Vehicle and Mission Control Systems were performed during the period from May 1995 to February 1996. Due to space limitations, only the results of the first sea trials conducted in Sines, Portugal with the objective of assessing the performance of the Mission Control System of MARIUS are reported below.

The test series included programming and running a simple mission example, whereby the vehicle was required to trace a square-shaped trajectory at constant depth and speed of 1.35m and 2.0m/s, respectively, in a fully autonomous mode. For safety reasons, during this initial test phase the vehicle was always operated at low depth. The square maneuver was obtained by requesting the vehicle to change its heading by -90° every 40 seconds. The initial heading was 0°.

The software tools for Mission Control introduced previously were used to program and run the mission described, which is embodied in the Petri net structure of Figure 11; see [14] for complete details. The design of the Mission Program involves a Mission Procedure named *HorizPath*, which parametrizes the action of keeping constant heading ψ, depth z, and speed u of the vehicle during a given period of time t. The corresponding calling header is $HorizPath(t,z,u,\psi,p_{MPEnd})$ where p_{MPEnd} denotes a specific place in the Petri net that is marked when certain conditions are met. The execution of this Mission Procedure entails the activation and synchronization of a number of Vehicle Primitives that include, among others, those in charge of steering the vehicle to the desired setpoints for depth, speed, and heading. The Mission Program shows four distinct phases.

In phase 1, all (Vehicle) System Tasks are initialized by calling a Vehicle Primitive named *Init*.

In phase 2, the *HorizPath* Mission Procedure is called for a period t = 20s, with a velocity set-point of u = 2m/s, a depth set-point of z = 1.35m, and a heading set-point of $\psi = 0°$. At the end of this phase, the vehicle is stabilized in depth and speed, heads north, and is ready to start the required square maneuver.

Phase 3 calls the *HorizPath* Mission Procedure repeatedly, with heading set-points of 0°, -90°, -180°, and -270°, while maintaining the remaining input set-points equal to those in phase 2. The required duration of each Mission Procedure call is t = 40s. In parallel, a Vehicle Primitive *ControlDataLog* is invoked to start logging control loop data for off-line analysis.

Finally, in phase 4 the vehicle is placed in manual mode. The logging of vehicle control data is stopped, and the mission ends normally if no errors are reported. Should an error occur during the mission, the place p_{Abort} is marked, and a *Reset* command is issued. This will bring the vehicle to the default manual mode, and the mission is aborted.

Throughout this simple mission, the vehicle pulled a buoy with an antenna, thus enabling radio communications between the vehicle and a support station. The software for Vehicle and Mission Control was run on the computer network installed on-board the AUV. The support station consisted of two IBM PCs running the MS Windows multi-task operating system, and a Vehicle Command Console. A man-machine interface named MUCIS (MARIUS-User Command Interface System) was developed for the tests, to enable manual remote control when required, and to assess the internal state of the vehicle and the state of progression of the mission during mission execution [16]. The PC dedicated to mission follow-up enabled displaying selected mission Petri nets, together with the respective marking sequences. Figures 12 through 14 display some of the data acquired in the course of the mission. Figures 12 and 13 show the commanded and measured heading, and the rudder activity, respectively. Figure 14 shows the slight variations in depth caused by the wave disturbances.

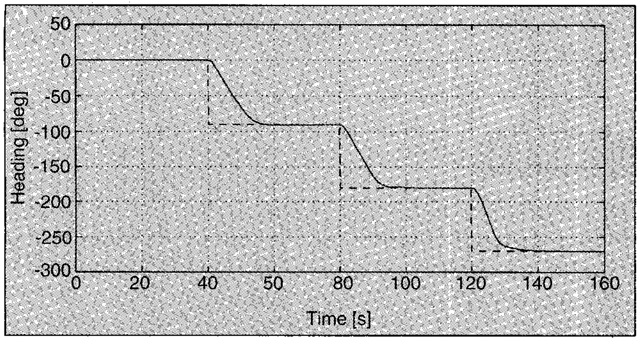

Figure 12. Commanded and measured heading.

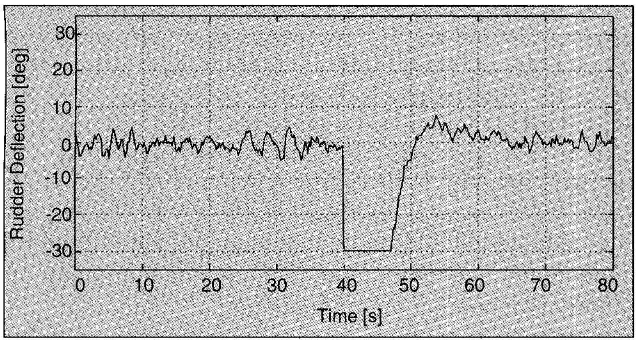

Figure 13. Rudder deflection.

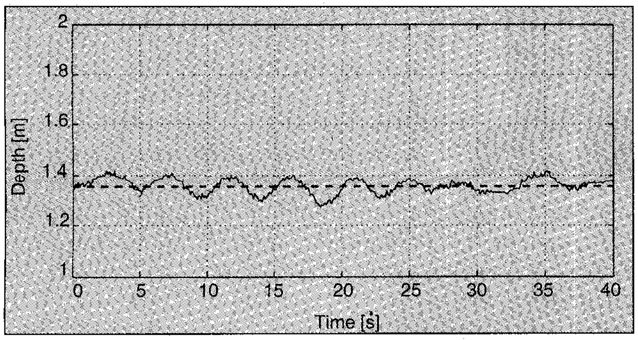

Figure 14. Commanded and measured depth.

CONCLUSIONS

A prototype autonomous underwater vehicle named MARIUS has been developed by a multidisciplinary team of scientists and engineers from Denmark, France, and Portugal, under the MAST Programme of the Commission of the European Communities. The primary envisioned missions of the vehicle are underwater inspection and ocean data acquisition in coastal areas. The research and development work carried out led to the integration and field testing of the main AUV systems for Vehicle and Mission Control, and paved the way for future activities in the challenging areas of Underwater Navigation and Mission Management.

In the course of the project, a number of scientific and technological problems were addressed and solved in a wide range of areas that included the following: i) vehicle design for optimal hydrodynamic performance, ii) integrated design of navigation, guidance, and control systems, iii) computer hardware and software architectures for real-time control, iv) multimodulation communication systems for reliable communication in shallow waters, v) mission control systems, vi) human-vehicle interfaces, vii) mission management systems for advanced mission execution and mission follow-up, and viii) hardware and software for real-time multibeam sonar interfacing and obstacle detection.

The results obtained have impacted on the definition of future European research and development programs in the area of underwater robotics, and are currently being exploited to foster the interest of commercial enterprises in the use of autonomous underwater vehicles for ocean exploration.

ACKNOWLEDGMENTS

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Systems, and Mission Control Systems with applications to Underwater Vehicles.

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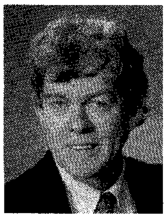
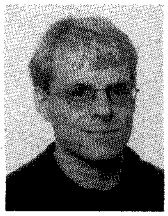
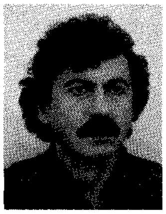


Anders Bjerrum has been involved in Autonomous Underwater Vehicle (AUV) development work at COWIconsult Consulting Engineers, Denmark since 1989. He joined MARIDAN as a General Manager in 1994. In 1995, he organized a Nordic AUV association called PING (Projects on Instrumentation, Navigation and Guidance Systems for AUVs). He also organized the first Nordic PING Symposium in Copenhagen, May 1996. He is also Chairman of the Danish Petroleum Society.



Anders Ishoy joined Reson A/S after receiving his M.Sc. degree in 1987. He has been the project manager for several Marine Science and Technology (MAST) projects since 1991, and the person responsible for developing the obstacle detection system for the MARIUS AUV. He joined Maridan ApS in 1995, to work on the development of a control system for the Martin AUV. Currently, he is also pursuing a Ph.D. degree at the Technical University of Denmark.



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SPECIAL ISSUE SPECIAL ISSUE SPECIAL ISSUE SPECIAL ISSUE SPECIAL ISSUE

IEEE Robotics and Automation Magazine

APPLIED VISUAL SERVOING

The objective of this special issue is to provide readers of the magazine a collection of application-oriented articles in visual servoing with an emphasis on experimental results. In the past, the economic benefits of laboratory-based visual servoing research performed under artificial conditions have often been in question, as there always seemed to be a better way of doing the "task." Recently, however, a number of "real world" applications of visual servoing are beginning to appear that are economically justifiable. For example, the use of continuous high resolution visual feedback to guide the assembly of microdevices is proving to be an effective strategy for dealing with the difficulties in modeling the complex microworld. In transportation systems, cameras are beginning to appear on vehicles to warn drivers of impending hazards, and it is only a matter of time before partial vehicle control will be transferred to the vision system. The special issue will try to highlight efforts such as these that employ visual servoing techniques. The papers are due by January 12, 1998 (please send them to one of the editors below and indicate that these papers are being submitted for this special issue). Notification of acceptance will be sent by June 1, 1998. Deadline for submitting the final copy of the manuscript to the editors of the special issue is August 1, 1998. The special issue is targeted for December 1998. All papers will be refereed as per the guidelines of the magazine. Please refer to the RAS website for detailed submission information(http://www. acim.usl.edu/RAS).

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