Operations with Multiple Autonomous Underwater Vehicles: the PISCIS Project

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***Abstract*— The goals, technical challenges, and activities of the project PISCIS – Multiple Autonomous Underwater Vehicles for Coastal and Environmental Field Studies – are reviewed in the context of the activities of the Underwater Systems and Technologies Laboratory from Porto University.**

I. INTRODUCTION

The future of humanity is deeply related to the quality of the bodies of water of the planet, and to the maintenance of their bio-diversity. However, we are still far from understanding the underlying phenomena. This is why researchers are actively studying this important source of life – water – in all of its forms. To do this, researchers need advanced technologies and the development of new concepts for data collection. Autonomous Underwater Vehicles (AUV) are one of these advanced technologies.

Autonomous Underwater Vehicles are small, unmanned, and untethered submersibles. They are intended to provide researchers with a simple, long-range, low-cost rapid response capability to collect pertinent environmental data. But this technology is still at its infancy: most of the deployments are made with expensive prototypes and we lack concepts of operation. In this paper we discuss these challenges in the context of the research being done at Underwater Systems and Technology Laboratory from Porto University on the development and deployment of low cost AUVs and technologies for oceanographic and environmental data collection, and also on concepts for the networked operation of multiple vehicles and systems. This research is supported by the PISCIS project. The project started in December 2002, has a total duration of 3 years, and is funded by PROGRAMA POCTI Medida 2.3. The PISCIS project concerns the design and implementation of a modular, advanced and low cost system for oceanographic data collection that includes two autonomous underwater vehicles, an acoustic positioning system, a docking station and modular sensing packages. The PISCIS system is configurable for applications in real time oceanography, bathymetry, underwater archaeology, and effluents monitoring.

The paper is organized as follows: in section II we present the Underwater Systems and Technology Laboratory (USTL) from Porto University; in section III we discuss the key systems and technologies developed at the USTL that led to the technological development behind the PISCIS system; in section IV we describe the vehicles designed and operated by the USTL; in section V we outline operation concepts and research avenues for the PISCIS system; and we conclude the paper with the conclusions in section VI.

II. UNDERWATER SYSTEMS AND TECHNOLOGY LAB

The Underwater Systems and Technology Laboratory (USTL) from Porto University was founded in 1997 to promote research, development, deployment, and operation of advanced systems and technologies in oceanographic and environment field studies. Today, USTL aggregates close to 20 researchers including Faculty, Ph.D. and M.Sc. students, and engineers.

The laboratory started developing and operating the *Isurus* AUV in 1997. Since then, USTL designed and developed: 1) Remotely Operated Vehicle (ROV) for the inspection of underwater structures; 2) low cost AUV for coastal oceanography; 3) low cost sensor modules for remote environmental data collection; 4) acoustic navigation technology for multiple AUVs; and 5) feasible concepts for the networked operation of multiple vehicles and systems.

USTL has been operating on a regular basis the AUVs, the ROV, and sensor modules networks in oceanographic field studies, inspection of underwater structures, biological field studies, and environmental data collection. In the summer of 2003, in collaboration with National Center for Underwater Archaeology (Centro Nacional de Arqueologia Subaquática), USTL will deploy both the *Isurus* AUV and the ROV in archaeological missions off the coast of Portugal.

III. TECHNOLOGICAL DEVELOPMENT

Technological development at USTL is guided by a vision for the networked operation of vehicles and systems for the next 10 years, and by a pragmatic approach to R&D and to operations. In our vision, the networked operation of vehicles and systems will change dramatically the way we approach oceanographic and environmental field studies (see [4]). Although we are still far from understanding the way this change will take place, it is not difficult to envision the operation of multiple vehicles within dense sensor and communication networks under the supervision of human operators and updating massive databases and prediction models. Recognizing that we are still taking the first steps in this direction, we have been actively involved with the potential users of networked vehicles and systems. This enables us to envision concepts for the operation of systems which could not have been imagined before. This is why we have a pragmatic approach to research and development, and to operations. We need to anticipate technological trends, to field test technologies, and to interact with scientists that will be using these technologies.

The USTL has developed several systems and technologies to be integrated in underwater vehicles and support equipment. Guided by our vision and by our pragmatism we have followed four main principles in our developments: 1) application oriented solutions taking into account the requirements of the potential end-users; 2) modular design, reconfigurable, and reusable open systems both in hardware and in software; 3) implementation of PC-based control using COTS technology; and 4) development of advanced navigation and control algorithms, squeezing the maximum performance out of the available sensors and actuators.

Following this strategy, the USTL has gained valuable technological expertise in a wide range of areas. It is now possible for researchers at USTL to design and build autonomous underwater vehicles at Porto University, and to conceive advanced concepts of operations for these vehicles.

Next, we briefly describe the key systems and technologies that led to the technological developments behind the PISCIS system.

A. *Computer system*

The standard computer system for each vehicle consists of a main PC-104 stack running the QNX real-time operating system. PC-104 is basically a repackaged, modular version of the standard PC in a reduced size form factor. QNX is a real-time extensible POSIX-certified OS with a small micro-kernel and a set of optional cooperating processes. This architecture allows us to scale QNX to the particular needs of each vehicle [8]. QNX provides most of the required functions for the execution of the vehicle software despite some deficiencies in thread support. An initial investment in the development of device drivers was required since most of the commercially available PC-104 boards do not have specific drivers for QNX. Today, USTL provides these services in the PC-104 market.

The onboard sensors are interfaced through I/O cards on the PC-104 bus: an A/D card and serial port cards. The PC-104 computer system runs the command, control and navigation software, from a hard or flash disk. A Windows based PC can be connected through an Ethernet cable to the onboard computer. In the ROV, the PC runs the operator console. The PC also runs a Web server providing Web-based access to data from operations, while ROV control is restricted to the operator console. Basically, this computer accepts high-level commands from the console, and informs the console about the state of the system. In the AUVs, the PC can be connected through an Ethernet cable or a wireless link to an operator console used for mission programming and debugging, and for data downloading at the end of a mission.

B. *Vehicle software*

The USTL designed and implemented the modular onboard software package that runs on each vehicle. This software is responsible for the control and navigation of the vehicle, and also for the command of payload sensors.

The software organization follows a hierarchical layered model, with well defined interfaces and access points. At each layer there are several agents running concurrently. Each agent manages a specific subsystem. This approach ensures functional separation, thus increasing code modularity. Each agent is implemented by a different process. In this way, it is quite simple to adapt the software for different vehicles and for different configurations of the same vehicle. The code was implemented in C++ and, although developed for QNX, it is almost system independent. In fact, the only requirement for the operating system is to support process based multi-tasking. The remaining features of the operating system (process scheduling, priorities, message passing, communications, service identification via names) are encapsulated in classes whose implementation can be adapted to different operating systems without any further change in the code. We have designed libraries of device drivers for sensors and actuators, and parameterized algorithms for control, guidance and fault management for each specific vehicle configuration.

C. *Acoustic navigation system*

Another major line of work of the USTL is the acoustic navigation system for multiple vehicles. Acoustic navigation is the most popular way of obtaining absolute positioning information in the underwater environment for non-military operations. The acoustic navigation system developed at the USTL is based on a technique known as long baseline navigation (LBL). This technique requires the deployment of a set of acoustic beacons, or transponders, in the area of operation, and the installation in the vehicle of an omni-directional transducer, capable of transmitting and receiving acoustic signals.

Fig. 1. Buoy with underwater acoustic beacon

Each vehicle interrogates each beacon, with a given frequency, and each transponder replies with another frequency. The vehicle computer system measures the time elapsed between the interrogation and the reply from the transponder to compute the distance to that transponder. Using a triangulation algorithm and knowing the locations of the beacons the position of the vehicle is then determined. The exchange of underwater acoustic signals requires an arrangement of elemental building blocks, namely an acoustic transmitter, an acoustic detector and an interface board. All these blocks have been developed at USTL and, currently, different configurations are being used on the AUV, the ROV and on navigation beacons.

D. Navigation system

The navigation system receives motion data from the navigation sensors and outputs an estimate of the state of the vehicle. We use several navigation sensor packages depending on the type of vehicle, and on the mission requirements (see [1], [7]). The AUVs are quite constrained in terms of space and power. The ROV is less constrained.

We mount the acoustic navigation system and a pressure sensor in both types of vehicles, AUV and ROV, to get global position data. The simplest configuration of the navigation sensor package includes, besides these two sensors, a magnetic compass, and a set of tilt sensors. Optionally, an inertial navigation unit and an acoustic Doppler velocimeter can be used. When the vehicle is far away from each transponder the time elapsed between consecutive position updates generated by the acoustic navigation system can be in the order of a few seconds[1]. In the meantime, the navigation system uses dead reckoning information, i.e., velocity and acceleration data, to update the position estimate. In the case of the *Isurus* AUV, the instantaneous velocity is obtained by measuring the propeller rotation speed and the vehicle heading, pitch and roll. Velocity measurements are fused together with range measurements by a Kalman filter based algorithm, taking advantage of the characteristics of each type of data: the vehicle velocity is available at a high rate, but its integration leads to a drift in the estimated position; the range measurements can be noisy, are available at a lower rate, but do not drift over time. The algorithm updates the estimate of the vehicle position at the same rate of the velocity updates, and corrects it whenever a new range measurement is available, giving the best estimated position in real-time [7]. Besides the estimation of the vehicle position, the algorithm also produces a coarse estimate of the water current (in the horizontal plane). In the case of the ROV, besides the pressure sensor and the magnetic compass, we use an inertial navigation unit (HG1700 from Honeywell) and an acoustic Doppler velocimeter (DVL Argonaut from Sontek). The angular velocities given by the inertial unit are directly used by the heading feedback control loop. The bottom tracking feature of the Doppler system gives the velocity relative to the bottom. This information as well as the information obtained form the inertial unit (linear accelerations and angular velocities) are then fused together with the data from the pressure sensor and the ranges to the transponders to provide an estimate of the vehicle position and attitude in real time. The data fusion algorithm is based on a Kalman filter.

E. Low-level control systems

The design of low-level control systems for underwater vehicles is a complex and challenging task. For example, the preparation and execution of missions for parameter identification is very resource consuming, and the existing models are usually inaccurate, particularly in the cases where the physical configuration of the vehicles changes frequently.

The USTL approach to low-level control design organizes the low-level control system in three main modules: user interface, trajectory generation and feedback control. The AUV and the ROV systems share the trajectory generation and feedback control modules. The user interface differs significantly. The ROV has two modes of interaction with the user: tele-operation – the operator pilots the ROV with a joystick – and tele-programming – the operator commands the execution of automated maneuvers. At this stage, the interactions between the *Isurus* AUV and the operator occur only at the mission planning phase. This situation will change in the PISCIS project with the introduction of acoustic modems. The acoustic communication technology will make it possible to tele-program our AUVs.

For trajectory generation we have been using techniques that take advantage of differential flatness property shared by our vehicles [6]. For feedback control design we have been using standard non-linear control techniques, since linear decoupled controllers typically result in poor performance.

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[1] The distance from the transponders can be in the order of few Km. The time elapsed between consecutive position updates is dictated by the time it takes a sound wave to travel from the vehicle to the transponder and from the transponder back to the vehicle.

F. Control architecture

We have been developing a control architecture to govern operations with multiple vehicles and systems. This is not a trivial matter. The problem of specification and design of coordinated control for new concepts for the operation of networked vehicle and sensor systems poses new challenges to control engineering ([3], [4], [5]). These challenges entail a shift in the focus of control theory - from prescribing and commanding the behavior of isolated systems to prescribing and commanding the behavior of distributed interacting systems - and requires a convergence of methods and techniques from control engineering, networking and computer science [9].

We organize the operations of our vehicles in terms of prototypical maneuvers. First we define a basic set of *atomic maneuvers*, from which all the maneuvers can be derived. Once we have found a minimal set of atomic maneuvers, we can verify their design for safety. We then compose complex maneuvers, using the elemental maneuvers as building blocks. This enables us to always design correct maneuvers - maneuvers that meet the given specifications - even in the presence of disturbances.

Until recently, we have designed and implemented maneuvers for one vehicle. Now we are designing coordinated maneuvers for teams of vehicles. In our setting, maneuvers can be designed to accommodate interactions with an operator, if that is feasible. For example, tele-operation for the ROV is defined as an atomic maneuver. In practical terms the maneuver encapsulates a pattern of interactions with: 1) low-level control and navigation systems; 2) trajectory generation modules; 3) sensors; 4) operator, if any; and 5) other vehicles and devices.

The modular design of maneuvers is mirrored by the modular design of controllers that govern the execution of a mission plan. The concept of mission plan does not preclude the intervention of operators. The main concepts in our modular design starting at the bottom of the control architecture are: *Vehicle controller* – controls the execution of a single vehicle maneuver (there is one controller per vehicle maneuver); *Vehicle supervisor* - it does not change throughout the life span of the vehicle, interfaces each vehicle with external control structures, and supervises the execution of vehicle maneuvers; *Team controller* - interfaces each team with any control structure (for example the plan supervisor), commands and monitors the execution of multi-vehicle maneuvers, and accepts and rejects commands to execute these maneuvers; *Team coordinator* - does for a team what the vehicle supervisor does for one vehicle, however it is is created and destroyed on the fly, and relies on a network of links to vehicle supervisors or to other team coordinators; *Plan supervisor* – supervises the execution of the mission plan, and commands the creation and destruction of team coordinators; *Mission plan* – a data structure defining a partial order on tasks or maneuvers to be executed by a set of vehicles and systems;

IV. VEHICLES AND MISSIONS

The USTL has been operating and developing the *Isurus* AUV, for the past 5 years [2]. *Isurus* (see figure 2) is a REMUS (Remote Environment Measuring UnitS) class AUV, built by the Woods Hole Oceanographic Institution, MA, USA [10]. These vehicles are low cost, lightweight, and specially designed for coastal waters monitoring . The reduced weight and dimensions makes them extremely easy to handle, requiring no special equipment for launching and recovery.

Fig. 2. *Isurus* autonomous underwater vehicle

Currently, *Isurus* integrates all of the technologies developed at USTL. *Isurus* has a torpedo shaped hull, about 1.6 meters long, with a diameter of 20 cm and weighting about 35 kg in air. The maximum forward speed is 4 knots, being the best energy efficiency achieved at about 2 knots. At this velocity, the energy provided by a set of rechargeable Lithium-Ion batteries may last for over 20 hours (i.e., over 40 nautical miles). *Isurus* can be configured for different types of missions. The basic configuration is summarized in the following table.

Sensors	OS200 CTD (Ocean sensors) Optical Backscatter (Wet Labs) SideScan Sonar (Marine Sonics) Altimeter (Imagenex)
Navigation	TCM2 Digital Compass (PNI) LBL Acoustic Beacons 20-30 Khz
Actuation	Propeller Horizontal and vertical fins
Computer system	PC104 Technology QNX real-time operating system

The first operational missions with *Isurus* took place in 1998, in the estuary of the river Minho, in the northern border between Portugal and Spain. The typical mission lasted over one hour and consisted of Conductivity, Temperature, Depth (CTD), and bathymetric data collection. These missions demonstrated the reliability and the operational effectiveness of this vehicle. Since then several other missions have been performed on different scenarios. Last summer, *Isurus* mapped the plume generated by a sea sewage outfall, 3 km off the Portuguese coast. The vehicle successfully performed a 2 hours mission, under very severe sea conditions. This innovative mission profile is now part of the monitoring plan for this sea outfall.

The experience accumulated with the operation of *Isurus* proved invaluable in the design of the new AUV generation that will be the USTL workhorse for the next five years. The new AUV is targeted for low cost and also to support multi-vehicle operations. The first field-tests will take place during the summer of 2003. The vehicle was designed and built at Porto University and integrates all of the technologies developed at USTL. The mechanical design was done in cooperation with mechanical engineers from INEGI. The main features of the new mechanical design are:

- Utilization of lighter composite materials in the central hull, saving valuable weight to incorporate new sensors and electronics.
- Increased modularity to ease the configuration of the vehicle for each type of missions to be performed.

The vehicle incorporates a radio link for wireless communication when the vehicle is at the surface, and mounts acoustic modems for underwater communications. The power management system converts the battery voltage to the voltage levels required by all of the electronic circuits and monitors, in real-time, their operation. It also provides an interface to the external battery charger.

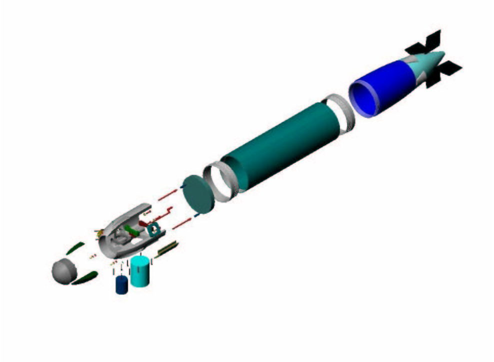

Fig. 3. New generation autonomous underwater vehicle

Remotely Operated Vehicles are unmanned and tethered submersibles piloted by a human operator. A ROV system usually consists of the ROV, a tether and the tether management system, and an operator console. The tether is used for information and power transmission. Typically ROVs are used in the real-time visual inspection of underwater structures, such as ship hulls, port structures, underwater pipe and cable systems.

The USTL has been developing and operating an ROV (see figure 4) for the last 3 years. This vehicle is being developed for the project Inspection of Underwater Structures (IES). The Inspection of Underwater Structures (IES) project concerns the design and implementation of an advanced low cost system for the inspection of underwater structures based on an ROV. The project started in 1999, had a total duration of 3 years, and was funded by PROGRAMA PRAXIS XXI - MEDIDA 3.1B, Portugal. The project partners are Porto Port Authority (Administração dos Portos do Douro e Leixões), Porto University (Faculdade de Engenharia da Universidade do Porto) and Institute for Systems and Robotics (Instituto de Sistemas e Robótica - Pólo do Porto). During the last phase of the project the IES system has been extensively used for several different inspection missions in the Leixões port. The IES system has successfully operated in near-zero visibility, taking high quality video footage of several underwater structures. In 2003 the system will be used in commercial operations ranging from inspection in harbors and dams to coastal underwater archaeological missions.

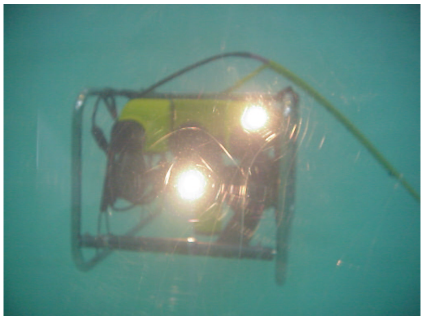

Fig. 4. Remotely Operated Vehicle for the inspection of underwater structures

Except for the ROV frame, hull and thrusters, that are a customized version of the Phantom 500 model from Deep Ocean Engineering, all of the other components and systems were designed and implemented at USTL. A new sealed cylinder has been installed to house electronics and sensors and the crash frame has been enlarged to 1.2 meters of length, 60 cm of height and 60 cm of width. Overall, the ROV weights about 100kg in air. The main characteristics of the IES system are summarized next.

Inspection system	Video Camera, Inspector (ROS) Pan and Tilt unit (Imenco) 600W of light (DSP&L)
Navigation	Argonaut Doppler Velocimeter (Sontek) Inertial Unit, HG1700 (Honeywell) Digital Compass, TCM2 (PNI) Acoustic Beacons, LBL 20-30KHz
Thrusters	4 DC Motors, 120V, 1/8 HP (Bodine)
Umbilical	Neutrally buoyant in fresh water Video, Ethernet and power (Falmat) 300 meters long Electrical slip ring at the surface
Computer System	PC-104 Technology QNX Real Time Operating System CAN Local Bus Ethernet interface with the console

The main innovations of the IES project with respect to commercially available ROV solutions are:

- *On-board power and computer systems.* This physical

and logical arrangement minimizes the number of wires in the tether cable thus minimizing drag and improving performance. Moreover, it allows for the modular configuration of the ROV hardware since additional thrusters and sensors are directly plugged to the ROV power and control systems.
- *Two modes of operation:* tele-operation and tele-programming. The tele-operation mode is a standard feature in ROV systems. The tele-programming mode enables the operator to program automated operations, such as trajectory or path tracking.
- *Integrated navigation.* The navigation system integrates data provided by an external acoustic system and by internal sensors for better control performance and position accuracy.
- *PC-based control.* Easy to use, COTS technology, low development and maintenance costs.

V. OPERATIONS

In the PISCIS project we will use the following enabling technologies for the coordinated operation of multiple vehicles and systems: RF and acoustic communications, and oceanographic sensor data in the low-level feedback loops. We are working on the software and hardware interfaces to integrate these technologies in our vehicles and systems. USTL is presently developing oceanographic buoys equipped with both RF communication and underwater acoustic communication devices, in addition to a large set of sensors. This way, these buoys can be used not only for oceanographic data acquisition, but also for AUVs navigation, and, most importantly, to support a communication network covering both surface vessels and AUVs. This communication network will allow real-time collection of data from different sources such as AUVs, buoys and Unmanned Air Vehicles at a single point, whether a land station or at a manned surface vessel. Additional data could be gathered at these central points via other communication links, e.g. the Internet or even satellites. The availability of virtually all of the necessary data in real time, will allow not only better real-time control and coordination of the vehicles and sensors in the field, but also for more informed decisions regarding the mission itself.

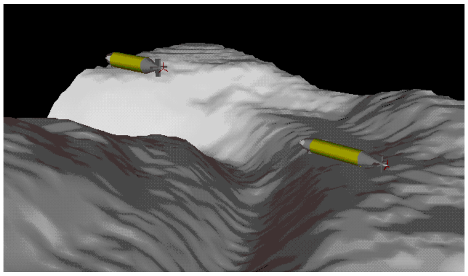

Fig. 5. Coordinated operation of multiple AUVs

At this stage of the project the planned operations concern:
- Conductivity, temperature, and depth sensor guided control of an AUV. The operational objective is to find in minimal time the plume generated by a sea sewage outfall with one AUV.
- Adaptive sampling of oceanographic phenomena with heterogeneous AUVs and other sensors[2]. The operational objective is to map a given region in minimal time.

VI. CONCLUSIONS

In this paper we have described the technological development behind the PISCIS project, outlined the research challenges, and described concepts of operation for networked autonomous underwater vehicles. We believe that the operational deployments of the PISCIS system will contribute to a better understanding of models and control concepts for the networked operation of autonomous vehicles. Finally, we also expect the project to yield more immediate practical benefits, namely in coastal oceanography and environmental studies.

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[2] The fundamental idea underlying adaptive sampling is to increase the survey efficiency by concentrating measurements in regions of interest. Thus, to map an oceanfront, for example, one might first run a very coarse survey to localize the front, and then concentrate operations in the front vicinity. Vehicles have limited communication capabilities, and coordination is restricted to the exchange of data and commands at pre-determined waypoints.