PISCIS: MULTIPLE AUTONOMOUS UNDERWATER VEHICLES FOR ENVIRONMENTAL AND OCEANOGRAPHIC FIELD STUDIES

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ABSTRACT

In this paper we describe the envisaged utilization of autonomous underwater vehicles (AUVs) under the PISCIS project. The aim of the project is to develop an integrated system for underwater data collection, particularly suited for environmental and oceanographic field studies. The Underwater Systems and Technology Lab (LSTS) at the University of Porto accumulated wide experience in the development and operation of small-size underwater robotic vehicles. Built upon this experience, the PISCIS project will be focused on the development of new technologies and methodologies to broaden the range of addressable operational scenarios.

INTRODUCTION

Traditional techniques for underwater observation are generally expensive and do not offer a comprehensive coverage, especially as the requirements become extremely demanding. On the other hand, recent progresses in underwater technologies have allowed for robotic systems to become highly versatile and, as a consequence, they have been increasingly adopted as efficient and effective tools for underwater observation and intervention.

The LSTS pursues the design and implementation of innovative approaches to underwater observation and intervention by the synergistic interaction between advanced topics in control with the latest developments in underwater technology. The laboratory has been involved in the design, development and operation of underwater robotic systems for the last 8 years.

The development of a multi-disciplinary and complex system has much to gain from the interaction with demanding potential end-users. The information gathered in the last years from the requirements of realistic missions proved to be invaluable for the improvement of the overall system performance. So far, the major achievements have emerged from a trade-off between this top-down perspective and a bottom-up approach driven by the constraints imposed by state-of-the-art technologies. At the same time, the laboratory has also identified other significant limitations that could hardly be overcome with local improvements in the existing systems; instead, they pointed out the necessity of new paradigms for systems integration and operation. The PISCIS project will tackle this challenge, by consolidating methodologies and technologies under a new paradigm for ocean sampling. This project concerns the design and implementation of a modular, advanced and low cost system for oceanographic data gathering that includes two autonomous underwater vehicles, an acoustic positioning system, a docking station and modular sensing packages.

In the following sections, we start by describing the key underwater systems developed at the LSTS, including the Isurus AUV, and we present a brief description of the operational mission already performed. In the remainder of the paper, we identify the main challenges expected for the PISCIS project and we provide the solutions envisaged to overcome them.

UNDERWATER TECHNOLOGY DEVELOPMENT

Underwater Systems

The PISCIS project integrates a set of innovative technologies and systems previously developed at the LSTS for the operation of a Remotely Operated Vehicle and for the operation of the Isurus AUV.

A major line of work in the LSTS is acoustic navigation, since it is the most popular way of obtaining absolute positioning information underwater. The acoustic navigation system developed at the LSTS is based on a technique usually known as *long baseline* navigation, or 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. During the operation, the vehicle interrogates each beacon with a given frequency and each transponder replies with another frequency. The vehicle measures the turn around time and computes the distance to that transponder. Using a triangulation algorithm and knowing the location of the beacons, the position of the vehicle is then determined – Matos (1999).

The laboratory has also put some effort in the design of advanced control architectures and the implementation of suitable control systems. The operations of our vehicles are organized as a sequence of 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. From the operator's perspective, this means having at his disposal a set of commands with which a complex mission can be planned and executed. The set of commands is designed to comply with the operational requirements while ensuring proper termination, or adequate fault handling – Silva (1999), Fraga (2001).

The design of subsystems to be integrated in AUVs has to pay particular attention to power consumption, since the limited amount of onboard energy is an extremely valuable asset. Thus, the laboratory has been involved in the design of efficient power and motor controllers.

The Isurus AUV

The LSTS has been customizing and operating the Isurus AUV, for the past 5 years – Cruz (1999). Isurus (Fig. 1) is a REMUS (Remote Environment Measuring UnitS) class AUV, built by the Woods Hole Oceanographic Institution, MA, USA, in 1997. These vehicles are low cost, lightweight, and specially designed for coastal waters monitoring – von Alt (1994). The reduced weight and dimensions makes them extremely easy to handle, requiring no special equipment for launching and recovery. Isurus has a torpedo shaped hull, about 1.5 meters long, with a diameter of 20 cm and weighting about 35 kg in air. Inside the hull, several subsystems have been improved or specifically developed at LSTS, contributing to the enhancement of the vehicle’s performance and reliability. 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).

Fig. 1 - The Isurus AUV at the surface

AUV MISSIONS

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. During autonomous missions, typically longer than one hour, the vehicle continuously collected CTD and bathymetric data, while navigating on a LBL transponder network. At the end of each mission, the vehicle was recovered and data was uploaded to a laptop computer for display and validation. As an example, Fig. 2 shows a bathymetry map of the river estuary, generated by the post processing of a mission data.

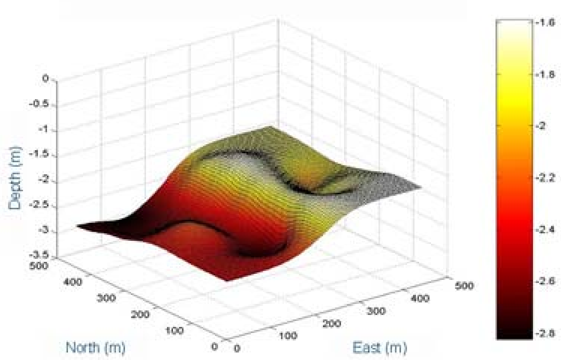

Fig. 2 - Bathymetry map of the river Minho

During the missions in the river Minho, the vehicle and the acoustic transponders were deployed and recovered by 2 people from a small fishing boat, which demonstrated the reliability and the operational effectiveness of the system – Cruz (1999). Since then, several other similar missions have been performed on different scenarios.
Another problem addressed with the Isurus AUV was the evaluation of the environmental impact of the heated discharge of a power plant located near the Crestuma dam in the river Douro. This included the influence in the mixing process of the river bed, the free surface and the interaction with bottom topography. For this analysis, the AUV was programmed to collect CTD data near the discharge outfall as well as bathymetric data – Ramos (2000).

Last summer, on an innovative mission, the vehicle was employed on a monitoring plan for a sewage outfall, 3 km off the Portuguese coast, near Aveiro. A simulation model was used in the first place to predict the location of the plume rising from the outfall, given the characteristics of the sewage and the surrounding water (density, current, etc.). The Isurus AUV was then programmed to collect CTD data at different depths in and out of the plume. Even under very severe sea conditions, with wave heights above 4 meters, the vehicle successfully performed the 2 hours mission according to plan – Ramos (2002). Fig. 3 illustrates temperature data, 2 and 4 meters bellow surface.

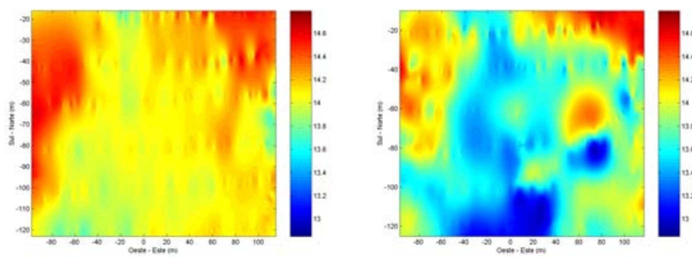

Fig. 3 - Temperature maps of the plume

THE PISCIS PROJECT

Project challenges

The PISCIS project started in December 2002, has a total duration of 3 years, and is funded by Programa POCTI Medida 2.3. PISCIS is a joint project involving the Administração dos Portos do Douro e Leixões (APDL), Faculdade de Engenharia da Universidade do Porto, Instituto Superior de Engenharia do Porto and Centro Interdisciplinar de Investigação Marinha e Ambiental (CIMAR).
APDL is the port authority in Porto and is mainly interested in operations in the vicinity of the harbors, involving sidescan sonar missions and other bottom topography studies. Researchers from CIMAR are particularly interested in oceanographic processes, thus requiring other classes of sensors. Overall, the PISCIS system has to be configurable for applications in real time oceanography, bathymetry, underwater archaeology, and effluents monitoring. Each AUV will integrate a set of relevant sensors for data collection, such as sidescan sonar, CTD, ADCP, fluorometer or other optical sensors. The envisaged accuracy of the navigation system also demands the incorporation of appropriate sensors, such as inertial units and Doppler velocimeters.
The coordinated motion of the vehicles supported by the docking station will allow for rapid ocean sampling, an essential requirement for the synoptic observation of oceanographic phenomena.
The most relevant technical challenges of this project can be summarized as:

- construction of a new autonomous underwater vehicle;
- simultaneous navigation of several vehicles in the same area of operation;
- coordinated operation of multiple vehicles; and
- specification and control of sensor based missions.

The LSTS Approach

The experience obtained from operational missions with the Isurus AUV allowed for an exhaustive characterization of the capabilities and limitations of the complete system. Cooperation with mechanical engineers from INEGI resulted in the identification of a set of key features to allow for significant improvements, resulting in a new design (Fig. 4) that is being assembled and is expected to be ready during the summer of 2003. These improvements in the mechanical design consist in:

- utilization of lighter composite materials in the central hull, saving valuable weight to incorporate new sensors and electronics;
- adoption of modular components for a rapid reconfiguration of the vehicle;
- incorporation of a radio link to allow for wireless communication when the vehicle is at the surface, avoiding recovery for data transfer.

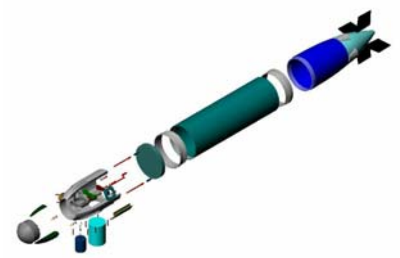

Fig. 4 - New AUV modular design

The navigation of several AUVs sharing the same acoustic network is a very active area of research. The navigation system of a single underwater vehicle usually combines information from on board dead reckoning sensors (that measure the vehicle velocities, attitude or acceleration), with absolute positioning information. This absolute positioning information is usually obtained from time of flight based range measurements to a set of acoustic devices deployed in the operational area – Matos (1999). Although this mode of operation is suitable for a single vehicle, its extension to the multiple vehicle scenario has only been done in very simple cases – Atwood (1995). Therefore, it still remains an open question the definition of efficient modes of operation of the acoustic network for the simultaneous navigation of multiple vehicles. The current navigation infrastructure of the LSTS composed by acoustic beacons – Cruz (2001) – and surface buoys (Fig. 5) will be upgraded to allow for the operation of multiple vehicles.

Fig. 5 - Surface buoy with underwater acoustic beacon

A framework for the representation, formal specification, and control synthesis for networked vehicle systems will be developed. The framework relies on techniques from set theory and dynamic optimization. First, we represent all entities, their dynamic behavior, and the relations among themselves. We use reachable sets to describe the evolution of a dynamic system, invariant sets to describe the locations where an entity is ensured to remain, and solvable sets to describe the locations from which a system can evolve to reach a given set. Second, we specify operations on these entities, and express the specification in a formal language. Third, we write partial plan specifications. Fourth, we define a planning procedure that results in a data structure defining all controller specifications preceding the controller design for which the logical relations are already satisfied. Fifth, we use techniques from dynamic optimization to synthesize controllers that either implement the plan, or prove that the plan is not feasible.
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 – Sousa (2001), Sousa (2002). 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 – Simsek (2001). The coordinated motion of the vehicles will be restricted to the exchange of data and commands at pre-determined waypoints due to the limited communication capabilities, imposed by the acoustic modems to be installed on the AUVs.

Finally, another thrust for this project is the problem of adaptive sampling of oceanographic phenomena with heterogeneous AUVs with limited capabilities. 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. Our paradigm is based on the assumption that there are ocean processes that can be approximated by simple models with time varying parameters. These models can be seen as temporal evolution of spatially distributed features. We will also explore the benefits of the coordinated operation of multiple AUVs to improve the efficiency of the sampling process.

CONCLUSION

In this paper, the AUV development program at the LSTS was reviewed in the context of the recent and exciting possibilities offered by the operation of networked vehicles and distributed sensor systems for oceanographic field studies. This review was organized in terms of the technologies developed at the laboratory and the way they can provide contributions to some of the most active research topics in underwater robotics.

Over the last years, the LSTS has accumulated valuable expertise in several areas related to underwater systems and is currently applying it to new projects with demanding requirements. One example is the PISCIS project, a low cost integrated system for rapid assessment of the underwater environment. The main challenges for this project were identified and so were the envisaged methods to tackle such challenges, in the shape of new paradigms for system integration and operation.

So far, the major technical developments at the laboratory have been driven by the requirements identified in real applications and most of the solutions obtained have actually been validated in successful operational missions. The same approach is intended for the new advances in underwater robotic systems and related technology under the PISCIS project.

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