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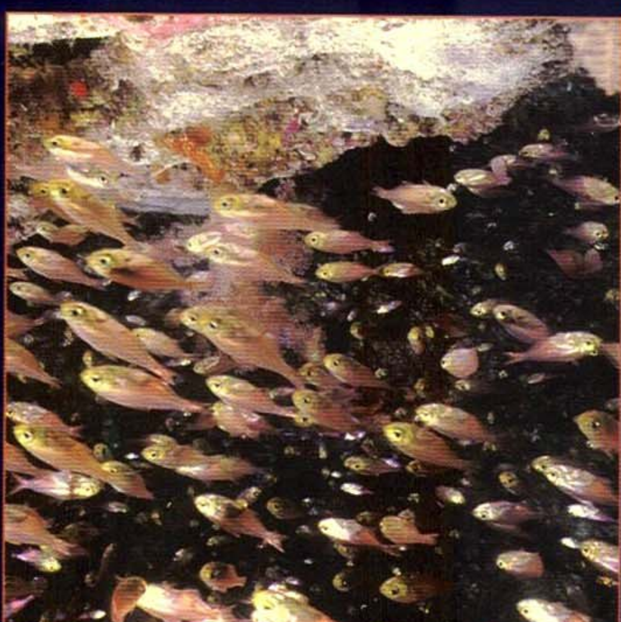

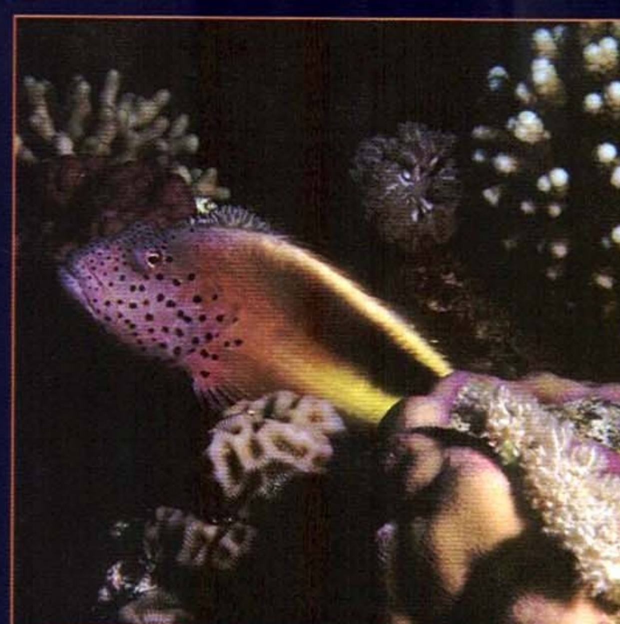

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SOMMARIO

Distributed sensor and vehicle networked systems for environmental applications

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Abstract

The recent and exciting possibilities offered by the operation of networked vehicles and distributed sensor systems are reviewed and their applications in environmental field studies are outlined.
Networked vehicle systems involving sea, air, and ground autonomous or operator-assisted vehicles are used as platforms for active sensing, such as adaptive sampling for oceanographic field studies.
Sensor networks combine data from spatially distributed sensor units which in addition to sensing capabilities have processing, power management, and communication capabilities. The cost of these sensor units is already in the order of some Euros and it is expected to reduce even further in a near future. This allows for the deployment of a high concentration of sensor units in a fairly large geographical area with acceptable costs. The combined operation of networked vehicles and sensor units allows researchers to envision ambitious environmental studies where, for example, a given geographical is monitored in real-time with adjustable resolution.
The review is done in the context of the research programme of the Underwater Systems and Technology Laboratory (USTL) from Porto University. Over the last two years the USTL devoted an intense effort to the development of feasible concepts for the networked operation of multiple vehicles and systems, and the first deployments are scheduled for late 2003.

Keywords

Sensor networks, autonomous underwater vehicles, networked vehicle systems, field studies

Introduction

The future of human beings is deeply related to the quality of the bodies of water of the planet, and to the maintenance of their biodiversity. However, we are still far from understanding the underlying phenomena. For example, what is the effect of pollution or of temperature variations on this particular species? How is an oil spill going to evolve and affect a coastal area? How are man-made underwater or surface discharges spreading, and how are they affecting the quality of the water we drink, the survival of this ecosystem, or the quality of our beaches?

Researchers are actively studying this important source of life, water, in all of its forms. In the last decades we have witnessed on the one hand, an increasing demand for environmental and oceanographic interventions, and on the other hand, the development of vehicles and technologies for intervention and data collection at seas, rivers, and lakes. The demand comes from scientists, trying to understand the effects of the human activities and to develop sustainable development and management policies; from commercial operations, trying to explore natural resources, such as oil and diamonds; from city and regional planners, trying to study the impact of new developments, such as floating airports; from marine archaeologists, trying to find sunken ships and submersed cities; and also from the military, trying to assert military dominance at the local or global level.

Shallow and coastal waters are accessible to humans for limited periods of time. Deep waters are still directly inaccessible for most countries. In both cases, we need technological advancements and the integration of existing technologies. Some of these technologies are still in their infancy, and most of the deployments are made with prototypes. Remote sensing and satellite imagery have been intensively utilized for the last decades and are quite unique in the services they provide for researchers. However, the information provided by these technologies has to be completed with field studies, both at the surface and underwater.

Two recent technologies are already proving as invaluable tools

for field studies: 1) autonomous and operator assisted vehicles, which are small unmanned vehicles that are either autonomous or operated remotely by a human, respectively; and 2) sensor networks [8], i.e. large sets of sensors each of which, in addition to sensing capabilities, has processing and communication capabilities. Both technologies allow for the observation of some physical phenomena in a way that was not possible before they were developed, and they can be deployed in combination to achieve even more detailed characterization of the phenomena under observation. For example, using sensor networks one can measure scalar or vector fields at several hundred points both in fairly small volumes as well as very large volumes.
In this paper we review this technology and describe the work that is being done at USTL on its development and deployment for environmental applications. It is organized as follows. In Section **Underwater Systems and Technology Laboratory**, we briefly present the research program of USTL. In Section **Technologies**, we discuss sensor networks and vehicle systems, and the main issues in their coordinated operation. In Section MISSIONS, we outline environmental field studies, some of them actually planned other conceivable in the near future, with the deployment of vehicle and sensor networks. We conclude in the last Section.

Underwater systems and technology laboratory

The Underwater Systems and Technology Laboratory (USTL) from Porto University has pioneered the development and integration of these technologies. Work in this area began in 97 with the operation of the ISUSUS autonomous underwater vehicle (AUV). Since then USTL designed and developed:

- Remotely Operated Vehicle (ROV) for the inspection of underwater structures.
- Low cost AUV for coastal oceanography.
- Low cost sensor modules for remote environmental data collection.
- Acoustic navigation technology for multiple AUVs.
- Operational concepts for the coordinated operation of multiple AUVs.

Over the last two years the USTL has worked hard on the development of feasible concepts for the networked operation of multiple vehicles and systems. More recently, researchers at USTL have been studying sensor networks and how they could be used together with networked vehicles to build on each other strengths. For example, networked vehicles can be used to deploy the sensor networks themselves, especially in areas where accessibility is difficult.
A result of this work is an ambitious joint program with the Portuguese Air Force with the following objectives: a) design and build an Unmanned Air Vehicle (UAV) that will work as a sensor platform;
b) develop the technologies for the operator assisted concurrent operation of multiple autonomo us vehicles and sensor networks.
Recognizing the multi-disciplinary nature of research on networked vehicles and systems, we devised a cooperative research strategy that is grounded on our experience in developing and deploying systems, and in our cooperation experience with leading institutions in the all these fields. We have been involved in fostering and growing a world-wide research community in this area. Since 2001 we have organized conferences, workshops, and invited sessions on networked multi-vehicles and systems.
Today USTL aggregates close to 20 researchers including Faculty, Ph.D. and M.Sc. students, and fulltime engineers. USTL operates on a regular basis the AUVs, the ROV, and sensor networks for oceanographic field studies, inspection of underwater structures, biological field studies, and environmental data collection. In 2003, in collaboration with National Centre for Underwater Archaeology, USTL will deploy both the ISUSUS and the ROV in archaeological missions off the coast of Portugal.

Technologies

This section provides an overview of the technologies underlying the research work at the USTL, and the main issues related to the coordinated control of multiple vehicles.

Sensor networks

Advances in microprocessors and in wireless networks originated a very recent, but also very active, research on sensor networks. A sensor network[8] is a set of sensors which, in addition to sensing capabilities, have processing and communication capabilities, making it possible to gather information collected by these sensors in a fairly large geographical area with acceptable costs. In fact, it is expected that the cost of these sensors will be around 1 Euro a piece, allowing the deployment of networks of hundreds or even thousands of sensors. The deployment of such large number of sensors allows the characterization of certain physical phenomena with a much larger detail than possible without sensor networks.
Sensor networks are still very recent technology and there are many research problems to address ranging from data communications techniques to application protocols and including routing of samples along the sensors in the network. Besides, most of the research on sensor networks has focused on electromagnetic wireless communications. This type of communication is not feasible underwater. In such an environment, the communication bandwidth is very low and a whole new set of protocols must be developed. Most of these problems are made harder by the scarcity of power.
However, in some cases, it may be possible to mitigate these problems, by combining sensor networks with networked vehicles.
The main function of a sensor network is to gather sensing data in real-time. Conventional communication paradigms and protocols are ill suited for this kind of application. For example, the publish/subscribe and event notification paradigms are more appropriate than the synchronous remote invocation. Indeed, the publish/subscribe paradigm fits better to the loosely coupled nature of sensor networks. For example, rather than polling a

thousand sensors for their values, one may request them once to notify any relevant value change. Yet another challenge are the real-time requirements of datasensing.
These may be important for event correlation or to allow real-time adaptation of the datacollection strategy, for example. Although the real-time requirements will depend on the phenomena under observation, it is an open question whether it is possible to develop communication protocols with real-time guarantees in large sensor networks.

Vehicles

Vehicles may be a valuable tool for environment monitoring. Mobility and the capability of autonomously make decisions on trajectories that optimize the gathering of more relevant data, distinguish them from the conventional motionless sensors and make them a most powerful tool.
The collected information can be correlated with other data collected from another devices, such as, oceanographic buoys, satellites, static sensors etc. However, when available, it is the data gathered by the vehicles that is usually more relevant.
Considering the area of operation, the nature of the collected data, the autonomy from human operators and the operational functionality, the vehicles in study can be characterized as follows:

- Autonomous Underwater Vehicles (AUVs) are small, unmanned, and untethered submersibles capable of executing missions autonomously, i.e., without the intervention of a human operator. Their main application is in gathering oceanographical data, integrating for this purpose a significant diversity of sensors. Being unmanned vehicles, with small dimensions, they have a great operability (transport and motion facility) and present low operation costs. Given that, they are autonomous vehicles, the use of AUVs groups makes it possible to gather data in large areas, in a relatively short interval of time, without human intervention. However, they have some technological limitations, namely power-autonomy, which is provided by on-board batteries, communications, which must be acoustic rather than electromagnetic, and navigation, witch cannot be relying on GPS for example, but requires both inertial and acoustic-based devices. Nevertheless, recent technological developments in this type of vehicles have increased significantly its potentiality. For example, recent acoustic modems make it possible to communicate in real-time with this type of vehicles, allowing for real-time data collection. This data can be used to make decisions on trajectories that optimize the gathering of more relevant data.
- Remotely Operated Vehicles (ROVs) are unmanned and tethered submersibles piloted by a human operator. An 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. The main application of these vehicles has been in real-time visual inspection of underwater structures, such as ship hulls, port structures, underwater pipe and cable systems. They have also been used in the observation of sunken ships or objects that in some way threaten the stability of the area where they are located.
- Unmanned Air Vehicles (UAVs) are unmanned, and untethered air vehicles capable of flying and executing segments of missions autonomously, i.e., without the intervention of a human operator.
  UAVs are able to carry a large variety of sensors, and can be used in aerial data acquisition, including imagery. Contrary to AUVs, UAVs are, in most cases, capable of transmitting data collected in realtime.
  Because of their small size and low weight, UAVs have high autonomy and can fly missions as long as 24 hours. Therefore UAVs make possible the aerial observation of large areas with low cost and minimum human effort. Some typical applications of UAVs are oil spills inspection and monitoring marine wild life.

Coordinated control

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 [1]. First, we require vehicles, devices, and controllers with evolving access capabilities to dynamically interact with each other, by exchanging messages and data, in order to execute tasks. Second, we need different notions of what should be observed under different circumstances, giving rise to questions of when two different systems exhibit the same behavior. Third, we need motion coordination models that are highly application dependent, and that may change with time for the same application. Fourth, we need to incorporate in analysis and control synthesis the aspects of communication and concurrency that are at the heart of these systems. Fifth, we need to consider data provisioning systems to manage and maintain representations of data exchanged with network-centric multi-vehicle systems. This challenge entails 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 [5]. From control systems topics of interest are the concepts and theories of optimality, stability, controlled invariance, and the motivation to improve the performance of increasingly complex physical processes. From computer science, the research has incorporated the theories of logical specification and verification, event-driven state machine models, process calculi, concurrent processes and languages, and object-oriented approaches. From networking topics of interest are ad-hoc networks, and mobility.
At USTL we have been working on a framework for the representation, formal specification, and control synthesis for networked vehicle systems [6,7], that we plan to extend to accommodate interactions with sensor networks.

Missions

In our work at USTL we are interested in abstracting, generalizing, and formalizing the issues related with the development of

unmanned vehicles and their operation both alone and networked. The understanding required for this endeavour must be grounded on applications from different fields.
Therefore, we have been actively involved with potential users of this technology in order to discuss concepts of operation, and new applications.
The following paragraphs outline some missions the USTL is preparing in order to better understand the issues related to the deployment of unmanned vehicles and sensor networks.
1. Increasing the resolution of oceanographic databases.
USTL in collaboration with other national and international institutions plans to conduct field experiments with multiple AUVs to investigate the potential for increasing the resolution of these databases. We plan to correlate this information with images taken from UAVs. These are long endurance missions, where we need to coordinate the motions of surface vessels that provide localization data to AUVs travelling a pre-determined path.
2. Coastal Ocean Outfall Plume Modelling.
The characterization of the dispersion of effluents from coastal ocean sewage outfalls is a difficult problem, and one requiring immediate attention as imposed by the EU legislation. Mathematical models provide some understanding of the processes that affect the dispersion of effluent plumes.
Nearfield models predict the initial characteristics, and are based on laboratory models of plume dynamics. Three-dimensional numerical models are used to predict the farfield plume dispersion under various oceanographic conditions. The verification of these predictions requires observations with accurate resolution and sufficient spatial coverage. This is not possible with traditional data collection methods. AUV sampling methods seem to provide the adequate temporal and spatial resolution for spatial mapping. Some field work has already been made in cooperation with a Portuguese wastewater treatment company [9]. The experiment took place in Aveiro and the aim was to study the environmental impact of sewage outfall plume. We employed one AUV in order to detect and map the effluent plume and to determine its dilution. In the future we plan to repeat the survey using not one but several AUVs and to correlate the information collected with images taken from UAVs.
3. Nowcast and forecast with distributed sensor networks.
We plan to have a deployable distributed sensor network to provide data in real-time for nowcast and forecast of oceanographic and environmental phenomena. For example, in sea outfalls the natural assimilative capacity of the ocean to dispose wastewater varies due to the great variability of the background water conditions. Studies will be conducted to predict the initial dilution and other wastefield characteristics from the data provided in real-time from a deployment of this sensor network in the Aveiro outfall. This information can be used by the treatment plant to control the discharge flowrate for minimal environmental impact.
4. Hybrid Acoustic and RF data telemetry networks
USTL is presently developing oceanographic buoys equipped with both RF commu nication 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 provide a data communications network covering both surface vessels and AUVs. This communications network will allow real-time collection of data from different sources such as AUVs, buoys and UAVs at a single point, whether a land station or 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 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 more informed decisions regarding the mission it self, thus making unmanned vehicles and sensor networks even more powerful and efficient tools for environmental data acquisition.

Conclusion

In this paper we have reported the work, both done and planned, at Underwater Systems and Technology Laboratory (USTL) on vehicle networked systems and distributed sensor networks. These technologies promise a new world of possibilities for the characterization of some environmental phenomena. However, in order to fulfill these promises the use of these technologies in the observation of environment phenomena must be better understood, and many research problems must be overcome. USTL has been working hard on the latter and has been actively looking for new opportunities to cooperate with potential users of the technology, both in academia and in the industry.

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