Towards a sustained presence in the ocean: sensor systems on networked vehicles

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Resumo: Este artigo descreve de uma forma geral o trabalho desenvolvido pelo Laboratório de Sistemas e Tecnologia Subaquática da Universidade do Porto desde a sua fundação em 1997. Em primeiro lugar, aborda-se a actual frota de veículos não tripulados do laboratório, que inclui também veículos aéreos. Segue-se uma breve descrição dos desafios associados à coordenação e controlo de sistemas de veículos que interagem entre si e com utilizadores através de redes inter-operadas. A abordagem do laboratório a esta problemática é apresentada nas perspectivas da arquitectura do sistema e das ferramentas de software para a sua implementação. Os sistemas recentemente desenvolvidos descritos na secção seguinte ilustram a facilidade de desenvolvimento de novos sistemas com base no know-how entretanto acumulado. Finalmente, os aspectos de operações com vários veículos são discutidos antes de se perspectivarem os trabalhos futuros nas conclusões.

Palavras chave: Unmanned Vehicles, Command and Control, AUV, ASV, UAV

1. INTRODUCTION

The Underwater Systems and Technologies Laboratory (LSTS) of Porto University has, since its foundation in 1997, been designing, building and operating unmanned underwater, surface and air vehicle systems for innovative applications with strong societal impact. Currently, LSTS has over 30 researchers, including faculty and students, with diverse backgrounds like Electrical and Computer Engineering, Mechanical Engineering and Computer Science. In 2006, LSTS received the national BES Innovation National Award for the design of the Light Autonomous Underwater Vehicle (AUV).

In the last 15 years, we have successfully deployed unmanned air, ground, surface and underwater vehicles in innovative operations in Europe and in the USA. These include some world firsts, such as the underwater rendezvous between the Aries and Isurus AUVs, respectively, from Naval Postgraduate School and Porto University, (Marques, 2007) that took place in 2006 in Monterey, California, under a cooperation project between both institutions. Currently, LSTS is leading several national and EU projects concerning the development of unmanned vehicle systems. The LSTS is tasked, under the Seacon project funded by the Portuguese Ministry of Defence (MDN), to deliver three units of an advanced version of the award-winning Light AUV to the Portuguese Navy. The LSTS is leading, in cooperation with the Portuguese Air Force Academy, the PITVANT unmanned air vehicle (UAV) program funded by MDN. LSTS is cooperating with the Portuguese Task Group for the Extension of the Continental Shelf (EMEPC) in the operation of the Deep Sea Remotely Operated Vehicle (ROV) Luso. LSTS is developing tools and technologies for ocean observation in the Raia project funded by the EU Program Cooperação Transfronteiriça Espanha-Portugal. In the EU FP7 project Control for Coordination, LSTS is developing coordination and control strategies to be demonstrated with oceangoing vehicles in 2011.

Fig. 1. LSTS unmanned vehicles.

Currently, the LSTS fleet includes two ROVs (rated for 200m and equipped with video cameras and side-scan sonar), two AUVs (1.8m long, equipped with side-scan sonar, acoustic modem and ADCP), six Light AUVs (1.5m long, configured with CTD sensor, side-scan sonar and acoustic modem), one autonomous surface vehicle (ASV) (can be used as a communications bridge between wireless and underwater communications), six UAVs (wingspans ranging from 1.8 m to 3.6 m), gateway buoys (supporting wireless and underwater communications) and sixty Telos Motes.

Section 2 outlines key research challenges addressed in the development of a framework for the systematic design and deployment of networked vehicle systems, being the LSTS approach sketched in Section 3. While section 4 outlines our planning and execution control framework, section 5 describes tools and technologies used for its implementation. Section 6 presents developments in fields such as Delay Tolerant Networks (DTNs), data loggers for oceanographic buoys, gateway buoys and wireless sensor networks. Section 7 discusses our operational deployments. Section 8 presents the conclusions and discusses future work.

2. RESEARCH CHALLENGES

LSTS is currently developing a scientific framework for the systematic design and deployment of cooperating networked vehicle and sensor systems in new applications with strong societal and scientific impact. These include persistent 24/7 operations. 24/7 system's level properties arise from the coordination and control of resources which are not continuously available due to operational constraints (e.g., fuel limitations). The idea of a system of systems enables us to capture the essential aspects of operation of these vehicle systems. In a system of systems, a significant part of the "system" is embodied not as physical devices, such as vehicles, sensors or communication networks, but as software applications which may be mobile. Moreover, mixed initiative systems, where operators intervene in the planning and control loops, play a central role in operations, thus making human factors an important design consideration. These challenges entail a shift in the focus of existing methodologies: from prescribing and commanding the behavior of isolated systems to prescribing and commanding the behavior of networked systems.

3. APPROACH

LSTS has a three-fold approach to these challenges: 1) low cost modular vehicles; 2) planning, command and control framework within which the interactions among heterogeneous vehicles, sensors and operators are standardized and mediated; and 3) a software tool set implementing the framework over inter-operated (possibly intermittent) communication networks. This inter-disciplinary effort builds on advances in (1) dynamic networks of hybrid automata; (2) hierarchical architecture design for semi-automated, distributed teams of agents; (3) incorporating human intervention in mission planning and execution; and (4) models of systems with evolving structure.

4. PLANNING AND EXECUTION CONTROL

Our layered approach to planning and control builds on a few concepts and lends itself to modular verification. In our developments, we have been considering mixed initiative interactions, enabling operators to intervene in the planning and control loops. In part this is because mathematical models cannot reflect essential experience and insight of these operators, and so these must approve or modify plans and their execution. Also, it is impossible to design vehicle and team controllers that can respond satisfactorily to every possible contingency. Our control architecture consists of two main layers: vehicle and multi-vehicle. Each layer is further decomposed into sub-layers. The vehicle control architecture is standard for all vehicles. The multi-vehicle control structure is mission dependent. The control architecture is formally described as interacting hybrid automata.

Vehicles are abstracted as providers of maneuvers and services, which are made available through standardized interfaces. Maneuvers are templates for motions and actions. Services include, for example, communications and computations. We use the concept of maneuver - prototype of an action/motion of a vehicle - as the atomic component of all execution concepts. Vehicle mission plans encode maneuver and service switching, as well as switching of control dependencies with respect to external controllers or operators. Conditions for maneuver and service switching, and for switching control dependencies, can be local to the vehicle, or coordinated with other vehicles, sensors, controllers or operators, possibly as a reaction to observed world state changes.

The vehicle control architecture consists of four layers. The lower level of the architecture abstracts sensors, actuators and communication devices. The maneuver control level consists of a library of maneuver controllers of which only one can be active at a time. The supervisory level consists of the vehicle supervisor, one per vehicle. The vehicle supervisor takes care of maneuver switching, service provision, communications, control dependencies in a dynamic multi-vehicle architecture, and error handling. The switching logic of the vehicle supervisor encodes guards on the internal state of the vehicle and communication channels (evolving over time). Some of these guards can be enabled/disabled in real-time with commands sent through dedicated communication channels to designated human operators. We allow and enforce access control by including access permissions for external controllers in the state of the vehicle. The supervisor also maintains and switches dependencies from external controllers with access permissions which are either in the mission plan, or changed in real-time.

The plan supervisory level consists of the plan supervisor, one per vehicle. The plan supervisor takes a mission plan as an input and supervises its execution. It triggers the execution of a specified maneuver and waits for either its completion an error. When the acknowledgement is received, the plan supervisor selects the next maneuver in the mission plan. The process is repeated until the plan is successfully terminated, or fails. System level plans encoding transitions among the combined states of the system and of the world are defined at higher abstraction levels. Transitions encode, for example, conditions on the number of vehicles required to accomplish a given goal, or on the world state. Control actions at this level may include the creation of control structures (controllers plus communication channels) to accomplish a given goal, or the migration of computations in a network. System level plans are executed by a structure of interacting controllers. Moreover, it allows the creation and deletion of structures of controllers, possibly interacting among themselves. This lends itself to the introduction of controllers of teams of vehicles which may also interact among themselves. An example of such interactions is load-balancing by switching vehicles among team controllers to compensate for unbalanced performance.

5. TOOLS AND TECHNOLOGIES

A comprehensive *toolchain* supporting the operation of heterogeneous vehicles has been developed.

Neptus (Dias *et al.* 2006) is a distributed command, control, communications and intelligence framework for operations with networked vehicles, systems, and human operators. Neptus supports all the phases of a mission life cycle: world representation, planning, simulation, execution, and post-mission analysis. Neptus supports concurrent operations with dynamic topologies: vehicles, operators, and operator consoles come and go; operators plan and supervise missions concurrently and control more than one vehicle at a time. IMC (Martins *et al.* 2009) is a communications protocol defining a common control message set for all types of LSTS nodes (vehicles, consoles or sensors) in networked environments. This provides for standard coupling of heterogeneous components in terms of data interchange. The DUNE onboard system is used to write generic embedded software at the heart of the vehicles, e.g. code for control, navigation, or to access sensors and actuators. It provides an operating-system and architecture independent C++ programming environ-ment for writing efficient real-time reactive tasks in modular fashion.

DFO (Data Flow Objects) is a coordination language for the specification of supervision control software, deployed on top of DUNE. It is used for supervision of mission execution, vehicle state, and embedding maneuver controllers. More expressive notions of autonomous vehicle execution – cooperative vehicle missions, dynamic exchange of control links between networked entities, and on-the-fly mission reprogramming – are being accommodated. Seaware (Marques *et al.* 2006) is an interface for publish-subscribe messaging, deployed on top of the Real-Time DDS tool. It supports dynamic coupling of network nodes and configurable QOS.

6. RECENT DEVELOPMENTS

Wireless sensor network (WSN) deployments for monitoring environment variables like temperature, humidity and noise levels have been deployed. Pilot experiments for wild-fire prevention (Sousa *et al.* 2006) and noise monitoring have been carried out. Data from these deployments is routed through an ad-hoc network of sensors into a base station that logs all data and provides real-time monitoring.

More recently, a web dissemination framework (Pinto *et al.* 2009) capable of receiving data from all LSTS devices and providing different means to access and visualize sensor data has been developed. Google Earth mashups to track the position of sensors and to analyse real-time data as seen in Figures 2 and 3, have been created.

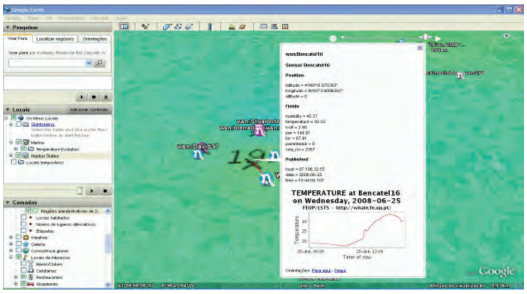

Fig. 2. Google Earth Mashup showing data from multiple WSNs

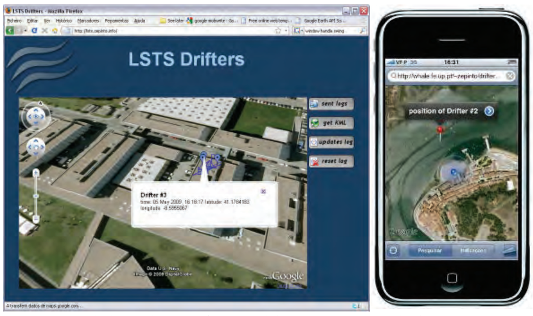

Fig. 3. Web-based consoles used for monitoring drifting sensors

We developed a DTN Convergence Layer for underwater acoustic modems and tested its feasibility in a joint demonstration with NURC. In this, we were able to successfully complete the transfer of data from a cellular phone aboard one ship to a laptop aboard another one by crossing multiple static and mobile acoustic modems subject to network disruptions. Oceanographic buoys have been instrumented with generic data loggers to register data gathered by multiple sensors (additional ones can be supported by a plug-in API). With only 3 watts, this device runs GNU/Linux with real-time extensions and uses a journaling file system for storing and accessing data (IMC and NetCDF 4 formats) from flash drives and optionally compress the data. The data logger has support for TCP, UDP and DTN2.

Moreover, we have been developing gateway buoys which are centralized communication hubs for maritime assets, supporting several types of WNs. These devices are capable of transparently route data between heterogeneous network links, balancing bandwidth and range. A HSDPA/GSM modem provides direct connection to the Internet in territorial waters, thus enabling real-time data publication in the World Wide Web. 2.4GHz and 5GHz Wi-Fi devices provide a low-cost solution for high-throughput and medium-range (4.5Km) communications and a 900MHz Carrier Class Modular Radio is used for longer-range links. An acoustic modem is installed for low-bandwidth and long-range underwater communications. Routing and store-and-forward is implemented with the aid of the DTN Reference Implementation.

7. OPERATIONS

The LSTS fleet has seen action at least twice a month since 2007. We have been operating in the Atlantic and Pacific and also in Portuguese and American rivers. Figure 4 depicts the setup of a demonstration which took place in 2008 at the Porto harbour in Portugal. Several AUVs and ASVs were operated under the control of our software *toolchain* over interoperated communication networks.

Fig. 4. Deployment with aquatic vehicles

Fig. 5. Air operations (Pitvant project)

Figure 5 presents photographs of UAV operations at the Ota Air Force base. These were carried out under the PITVANT project. In 2009, we accumulated over 100 autonomous flights with 6 different UAV platforms and performed a demonstration in the Douro River with coordinated operation between one ASV and two AUVs (Martins 2009). In 2010, we performed night operations at Sintra Air Force base and new operations are planned to test and certify novel developments, including new mixed initiative features, such as control handover between operators, target tracking and vision based control. Demonstrations of cooperating air and ocean going vehicle systems in collaboration with the Portuguese Navy and Air Force are planned in July in Portugal.

8. CONCLUSIONS

An overview of the R&D undertaken at the LSTS was presented. The theoretic framework for the coordination and control of networked vehicle systems was outlined along with a description of the tools and technologies being used to deploy it. The accumulated experience and know-how facilitate the rapid development of new systems for hydrographic applications. Innovative operations, including some world firsts, provide the motivation to conceive and deploy systems which could not have been imagined one decade ago. Our goal is a sustained and sustainable presence in the ocean.

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REFERENCES

Marques E., Pinto J., Kragelund S., Dias P., Madureira L., Sousa A., Correia M., Ferreira H., Gonçalves R., Martins R., Horner D., Healey A., Gonçalves G., Sousa J., "AUV Control and Communication using Underwater Acoustic Networks",*Oceans07, Aberdeen, Scotland, 2007.*

Pereira E., Almeida P., Morgado J., Coutinho D., Bencatel R., Gonçalves G., Sousa, J. "Apollo framework for UAV Systems: experimental results", *UAV Conf. 07, Paris, France, 2007.*

Dias P., Pereira F., Gonçalves G., Gomes R., Pinto J., Fraga S., Sousa J. "Mission Planning and Specification in the Neptus Framework", *ICRA 06, Orlando, USA, 2006.*

Sousa A., Gonçalves G., Sousa J., Pinto J., Lebres P., "Pilot Experiment of an Early Warning Fire Detection System", *EWSN'06, Zurich, Switzerland, 2006.*

Marques E., Gonçalves G., Sousa J., "Seaware: A Publish/Subscribe Communications Middleware for Networked Vehicle Systems". *MCMC'06: 7th IFAC Conf. on Manoeuvring and Control of Marine Craft, Lisbon, Portugal, 2006.*

Martins R., Marques E., Dias P., Pinto J., Sousa J., "IMC – A Communication Protocol for Networked Vehicles and Sensors", *IEEE Oceans 09, Bremen, Germany, 2009.*

Pinto J., Dias P., Gonçalves R., Sousa J., "Large Scale Data Collection Using Networks of Heterogeneous Vehicles and Sensors", *IEEE Oceans'09, Bremen, Germany, 2009.*

Martins R., Dias P., Pinto J., P. Sujit, Sousa J., "Multiple Underwater Vehicle Coordination for Ocean Exploration", *Int. Joint Conf. on Artificial Intelligence (IJCAI), Pasadena, USA, 2009.*