OPERATIONS AND CONTROL OF UNMANNED UNDERWATER VEHICLES

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Abstract: Operations and control of unmanned underwater vehicle systems are discussed in terms of systems and technologies, vehicles, operational deployments and concepts of operation. The notions underlying the specification of single vehicle operations are contrasted to new concepts of operation to illustrate the challenges they pose to control engineering. New research directions are discussed in the context of the theories and techniques from dynamic optimization and computer science. The overall discussion is done in the context of the activities of the Underwater Systems and Technology Laboratory from Porto University.

Keywords: Autonomous Underwater Vehicles, Remotely Operated Vehicles, Control, Navigation, Dynamic Optimization, Networked Vehicle Systems.

1. INTRODUCTION

The last decades have witnessed an increasing demand for environmental and oceanographic field studies and interventions. The demand comes from scientists, trying to model and understand natural phenomena; from planners, trying to understand the effects of human activities and to implement sustainable development policies; from commercial companies, trying to explore natural resources and to build underwater structures; from marine archaeologists, trying to find sunken ships and submersed cities; and also from the military, trying new approaches to underwater warfare.

Traditionally, interventions in the underwater milieu have been conducted by human divers. But the physiology of the human body imposes severe constraints on these interventions. This is why in the last decades, and driven by commercial, military and scientific applications, research institutions and commercial companies have developed and deployed remotely operated vehicles (ROV) and, more recently, autonomous underwater vehicles (AUV).

The development and deployment of unmanned underwater vehicles has contributed to the development and, in some cases, to field-tests of paradigms, vehicles and sensor systems for oceanographic and environmental data collection. One paradigm developed by researchers in the United States that has received significant attention is the Autonomous Ocean Sampling Network (AOSN) (Curtin *et al.*, 1993).

One of the next steps in research and development concerns systems integration, and development and deployment of concepts of operation. In turn, concepts of operation depend on technological limitations, and also on the nature of underwater operations.

Technological limitations. The major technological limitations come from energy storage, navigation, and communication technologies. Power is generally provided by on-board batteries; communications must be acoustic rather than electromagnetic; and navigation, which cannot rely on GPS, uses both inertial and acoustic-based devices. Inertial navigation devices are rather expensive and bulky. Acoustic-based devices provide reasonable global position estimates but typically require the deployment of a network of acoustic transponders.

Underwater operations. The nature of underwater operations typically involves deployments in areas commensurate to the scales of natural phenomena and of man-made interventions (including ecological disasters). This usually means that operations take place in large geographic areas over extended periods of time. The problem of scale is aggravated by the simple fact that, in general, sensing and/or intervention are local in nature. Except for a few sensor devices, such as side-scans, most sensors measure the value of a scalar variable at a geographic location. This is why the problem of data collection of non-stationary oceanographic phenomena is a difficult one. This problem and the issue of temporal aliasing are discussed in (Willcox *et al.*, 2001), and related to the concept of adaptive sampling introduced in (Curtin *et al.*, 1993). The fundamental idea underlying adaptive sampling is to increase the survey efficiency by concentrating measurements in regions of interest.

The technological limitations and the nature of underwater operations are often cited to explain the interest of researchers in the operation of multiple vehicles. For example, in (Willcox *et al.*, 2001) it is presented an analytical study which demonstrates that, for ocean sampling applications, more vehicles result, on the one hand, in significant reductions in power consumption and, on the other hand, in a reduction of temporal aliasing for the sampled data.

In most concepts of operation, the net effect of going from a single vehicle to multiple vehicles is merely proportional to the number of vehicles. For example, two vehicles duplicate the distance travelled by a single one during a certain time period. The notions underlying the specification of the corresponding operational deployments are: trajectories, way points, and sensor control. In summary, there is no explicit treatment of synergistic interactions among vehicles in the system.

In contrast, new concepts of operation involve the explicit control of synergistic interactions among vehicles in a system ((de Sousa and Pereira, 2002*b*; de Sousa *et al.*, 2002; de Sousa and Sengupta, 2001)). In these concepts, the notion of single vehicle becomes secondary when these synergistic interactions take place, and a system with entirely new properties emerges from them. The new notions are: service, interaction or connection, configuration, service region, and the composition of services. This means that coordination and control take place at a higher level of abstraction than before. The specification of operational deployments entails abstracting away technological details to capture the essence of interactions, of their purpose, and of rules that govern them. This introduces new elements in control design: 1) the available controls include the usual vehicle controls, links among vehicles and other devices, and the allocation of roles to vehicles; 2) the control constraints include, besides the traditional ones, rules for linking vehicles, and rules for allocating vehicles to roles; 3) the control objectives include the delivery of services in a region, and the implementation of algorithms, to name just a few.

Coordination and control at this level of abstraction pose new challenges to control engineering. In fact, it requires a convergence of methods and notions from control engineering, computer science and communications. The challenges come from the distributed nature of the problem: in networked multi-vehicle systems information and commands are exchanged among multiple vehicles and the roles, relative positions, and dependencies of those vehicles change during operations (see (Varaiya *et al.*, 2001) for a discussion on distributed control of hybrid systems).

This paper discusses underwater systems and technologies and new concepts for the coordination and control of multi-vehicle systems in the context of research and development at the **U**nderwater **S**ystems and **T**echnology **L**aboratory (USTL) from Porto University.

The paper is organized as follows. Section 2 presents a description of the USTL, emphasizing the research and development strategy and projects. Section 3 describes single vehicle operations and discusses control systems for these vehicles. Section 4 discusses concepts of operations and control of networked vehicle systems to illustrate new notions for the operation of networked vehicles, and to highlight the main differences with respect to single-vehicle operations. Finally, section 5 summarizes the conclusions.

2. UNDERWATER SYSTEMS AND TECHNOLOGY LAB

2.1 Background

The Underwater Systems and Technology Laboratory 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 USTL has an inter-disciplinary approach for the design, implementation, and deployment of networked vehicle systems for oceanographic and environmental field studies. This involves a technology push driven by engineers at the Faculty of Engineering and an application pull driven by biologists, oceanographers, geologists and environmental experts from the Faculties of Engineering, Medicine, and Sciences. The application pull is driven by scientists from Porto University in articulation with national and international research institutions; this articulation is done through CIMAR (the largest Portuguese center for marine research), the Portuguese Environmental agency, Porto Harbour Authority, and SMEs in the environmental services area. Research and development is targeted at developing and integrating tools and technologies for new applications. The core tools and technologies are being developed at the Underwater Systems and Technology Laboratory (USTL) at Porto University. These include: 1) autonomous and operator assisted vehicles, which are small unmanned vehicles that are either autonomous or operated remotely by a human; and 2) sensor networks, i.e. large sets of sensors each of which, in addition to sensing capabilities, have processing and communication capabilities. The USTL hs been operating the ISUSUS autonomous underwater vehicle (AUV) since 1997 (See http://dceg.fe.up.pt/ lsts/Arca-Prize-LSTS/ for details.). Since then we designed and developed: 1) Remotely Operated Vehicle (ROV) for the inspection of underwater structures; 2) low cost AUV for coastal oceanography; 3) accoustic navigation technology for multiple AUVs; 4) operational concepts for the coordinated operation of multiple AUVs; 5) multi-purpose Autonomous Surface Vehicle; and 6) sensor modules for environmental data collection.

Understanding that networked vehicle systems will change dramatically the way scientists approach oceanographic and environmental field studies (see (de Sousa and Pereira, 2002*b*)), researchers at USTL have defined the design, test and deployment of new concepts of operation as the main strategic R&D goal for the next 5 years. Recognizing that the R&D community is still taking the first steps in this direction, researchers at the USTL track technological trends, field test new technologies, and interact with scientists and end-users that will be using these technologies. This enables them to envision concepts for the operation of systems which could not have been imagined before, and to identify new research and development directions.

2.2 Projects

USTL has a strategic partnership with Porto Port Authority – **A**dministração dos **P**ortos do **D**ouro e **L**eixões (APDL) – and with Centre of Marine and Environmental Research – **C**entro de **I**nvestigação **M**arinha e **A**mbiental (CIMAR) – to develop vehicles and systems for underwater operations. Under this partnership, requirements are identified, and engineering and technological solutions are proposed, and projects are executed and technological transfer to APDL and CIMAR is promoted. This is done in close cooperation with Portuguese and European funding agencies. The IES, KOS, and PISCIS projects, described next, are representative examples of the implementation of technological solutions.

The Inspection of Underwater Structures (IES) project concerned the design and implementation of an advanced low cost system for the inspection of underwater structures based on a ROV (Cruz *et al.*, 1999). 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 APDL, Porto University – Faculdade de Engenharia da Universidade do Porto – and Institute for Systems and Robotics – Pólo do Porto do Instituto de Sistemas e Robótica (ISR).

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

On-board power system. In traditional ROV systems the tether cable includes a pair of power lines for each motor. The IES tether cable uses only 4 wires for power. The onboard power system distributes power to all of ROV devices, including motors. This physical and logical arrangement minimizes the number of wires in the tether cable thus minimizing the corresponding unmodelled disturbance and improving performance. Moreover, it allows for the modular configuration of the ROV hardware since additional thrusters and sensors are directly plugged onto 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 from the acoustic navigation system and from internal sensors for improved position accuracy and control performance.

PC-based control. The ROV is controlled by two commercial-off-the-shelve (COTS) computer systems: onboard computer and operator console. The onboard computer interfaces with all of the internal ROV devices and communicates through a Ethernet cable to the operator console.

The IES project was successfully completed in 2002. The system is now fully operational and it is being used in operations to inspect harbors and dams.

The Kit for Underwater Operations (KOS) project concerns the design and implementation of a modular, advanced and low cost system for underwater intervention and inspection. The system includes a robotic arm and inspection sensors. The project started in March 2004, has a total duration of 2 years and is funded by Agência de Inovação under Programa POCTI Medida 2.3. The project partners are APDL, Porto University and ISEP.

The PISCIS – Multiple Autonomous Underwater Vehicles for Coastal and Environmental Field Studies – project concerns the design and implementation of a modular, advanced and low cost system for oceanographic data collection. The concepts of operation and control are discussed in section 4. The PISCIS system includes two autonomous underwater vehicles, an acoustic navigation system, a docking station and modular sensing packages. The PISCIS system is configurable for applications in real time oceanography, bathymetry, underwater archaeology, and mapping of discharge plumes. The project started in December 2002, has a total duration of 3 years and is funded by Programa POSI Medida 2.3. The project partners are APDL, Porto University and CIMAR. Civil engineers from APDL, and marine biologists and animal physiologists from CIMAR are providing requirements and will test and validate concepts of operation and components of the PISCIS system.

3. SINGLE VEHICLE SYSTEMS OPERATIONS & CONTROL

3.1 Introduction

Typical AUV and ROV operation profiles are strongly dependent on their sensor payload, and on the operational environment.

The operational environment for the ROV is typically structured: underwater structures. The primary inspection sensor in the IES and KOS systems is a video camera, and the secondary sensors are a pencil beam sonar and an altimeter. From the control point of view, ROV inspections consist in one of the following: 1) simultaneous stabilization (in some or in all degrees of freedom) of the ROV and of the camera pan-&-tilt; 2) teleoperated exploratory motions to assess the state of underwater structures; 3) pre-defined motion patterns along walls or other structures; and 4) motions to the site of operations.

The operational environment for the USTL AUVs is typically unstructured: open sea or rivers (see for example (Willcox *et al.*, 2001; Carder *et al.*, 2001; Dhanak *et al.*, 2001) for details on mission requirements). The primary sensors are the conductivity, temperature and depth sensor (CTD), the side-scan sonar and the altimeter, and the secondary sensors are the video camera and the backscatter sonar. Typical missions are CTD runs or side-scan surveys. From the control point of view, these missions consist in following a predefined path or trajectory. The specifications for the accuracy of path or trajectory tracking depend on the type of the mission. For example, for CTD runs, the accuracy in the vertical direction is in the order of a few cms, while in the horizontal plane it is in the order of 1-2 m.

3.2 Control architecture

It is convenient to separate the mission specification from the actual control code: the mission specialist is not required to be familiar with the details of the control code; and the vehicle should be capable of executing different missions specifications with the same control code.

Informally, the mission specialist reasons in terms of prototypical maneuvers when it comes to mission specification. The types of ROV maneuvers are: *hover*, *followtrajectory*, *followfeature*, *surface*, *goto* and *tele-operation*. The types of AUV maneuvers are: *goto*, *followtrajectory* and *surface*.

The concept of maneuver plays a central role in the USTL control architecture: it facilitates the task of mission specification, since it is easily understood by a mission specialist; it is easily mapped onto self-contained controllers, since it encodes the control logic; and it is a key element in modular design, since it defines clear interfaces to other control elements.

The plan (or mission) specification is a data structure consisting of maneuver specifications, ordering constraints, variable binding constraints, and causal links.

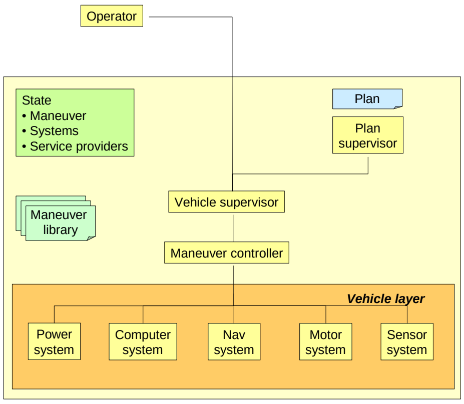

Fig. 1. USTL reference control architecture

The USTL reference control architecture for single vehicle operation is depicted in figure 1. Each element in the architecture is modelled as a hybrid automaton. These interact through the exchange of typed events: messages and commands.

At the bottom of the architecture there is the vehicle layer. This layer abstracts the interactions with the vehicle sensors and actuators in a modular interface. At the top of the architecture there is the plan (or mission) supervisor. The plan supervisor commands and controls the execution of the mission plan. It commands the vehicle supervisor to trigger the execution of a maneuver specification and waits for the acknowledgment of its completion, or for an error. When it receives the acknowledgement, the plan supervisor selects the next maneuver to be executed. The process is repeated until the plan is successfully terminated, or it fails.

The vehicle supervisor is depicted in figure 2. It has 4 states – *Init, Exec, Error, and Idle* – and a labelled transition system. Each transition is labelled with a guard, the condition under which the transition can take place, and an event, the message sent out when the transition is taken; the two are separated by a / in the figure. The vehicle supervisor is initially in the state *Idle*. Upon the reception of a maneuver specification it creates a maneuver controller if the *enabling* condition is true (this means that all of the vehicle systems are GO). Otherwise, the transition to the *fail state* is taken, and it sends an *error(code)* event to the plan supervisor, and the plan fails.

The *goto* maneuver controller described next illustrates the structure and operation of a maneuver controller. It has 5 states, *Init, Exec, Error, Done, and Stop*, and a labelled transition system. The *goto* maneuver controller enters the state *Init* immediately after being created by the vehicle supervisor. The transition to the *Exec* state is taken immediately if the condition *Init_ok* is true. If not, the transition to the *Error* state is taken and the event *error(code)* is sent to vehicle supervisor. In the *Exec* state, the vehicle supervisor uses the outputs of the navigation system and a low-level controller – a regulation law. When the location of the *goto* specification is reached with a pre-specified tolerance the transition to *Done* is taken and the event *done* is sent to the vehicle supervisor. Finally, the transition to *Stop* is taken immediately and the maneuver controller is deleted. The maneuver controller accepts an abort command from the plan supervisor or from the operator in any of its states. If this is the case it takes the transition to *Stop* immediately.

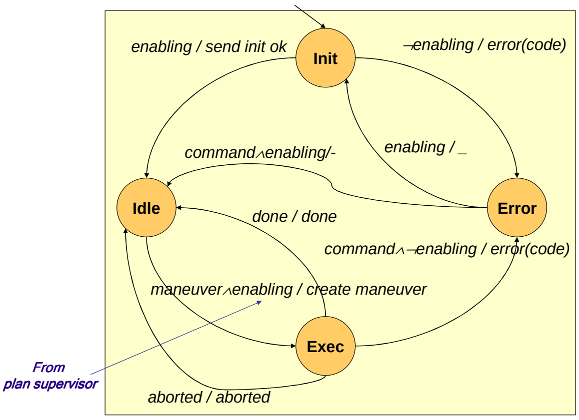

Fig. 2. Vehicle supervisor

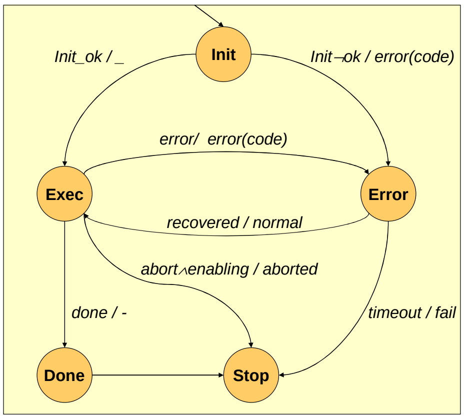

Fig. 3. *goto* maneuver controller

It is quite simple to extend the vehicle capabilities with new maneuvers. This does not require changes in the control architecture and on its software implementation.

The AUV onboard software implements all of the elements of the control architecture. The ROV implementation does not include the plan supervisor: the operator interacts directly with the vehicle supervisor. Related work on control and interaction protocols can be found in ((Phoha *et al.*, 2001; Turner and Turner, 2001)).

Notice that *tele-operation* is one of the ROV maneuvers. The corresponding maneuver controller allows the operator to pilot the vehicle, but the overall operation is under the control of the vehicle supervisor. This prevents the ROV from entering unsafe modes of operation.

4. MULTI VEHICLE OPERATIONS & CONTROL

4.1 Operations

The PISCIS project proposes several experimental challenges for networked vehicles and systems: 1) gradient descent in a scalar field; 2) mixed initiative interactions (operator-in-the-control-loop); and 3) finding the minimum of a scalar field. These challenges are intended to evaluate how synergistic interactions can be used to overcome technological limitations, and to identify useful concepts for specification, control synthesis, and execution.

As an illustrative example, consider the problem of finding the maximum of a scalar quantity. An instance of this problem consists in locating a thermal vent within an area of several square kilometers. The operational deployment consists of several AUVs equipped with acoustic modems, buoys for acoustic localization, underwater and RF communications, and an operator console.

Researchers at USTL have been working on several optimization based strategies for search and gradient following (de Sousa and Pereira, 2002*a*). Lyapounov methods are proposed in ((Leonard and Fiorelli, 2001; Bachmayer and Leonard, 2002; Fiorelli *et al.*, 2003)) to derive gradient descent controllers for underwater vehicles, and an operational deployment with underwater gliders (Webb *et al.*, 2001) is scheduled for the summer of 2003 (Fiorelli *et al.*, 2003). In these approaches, the vehicles are coordinated to both estimate and follow the gradient. The issue of fusing data collected by several vehicles is discussed in (Leonard and Feder, 2001).

The specification, control synthesis, and execution of an optimization-based search algorithm requires a precise definition of constraints, interactions, and objectives. This is done next with the help of predicate logic.

There are three types of entities in this operational deployment: AUVs, buoys, and console. These entities provide atomic services.

An atomic service is a service that does not result from the composition of other services. The buoys provide the following atomic services: underwater communications, CTD sensor, beacon, and RF communications. The AUVs provide the following atomic services: underwater and RF communications, CTD sensor, and motion. The beacon service is available within a circle centered at the beacon. The RF communication service is available only at the surface.

Any two entities can interact through an atomic link. An atomic link is a relation on the positions, motions, interactions, and atomic services provided by two entities. Following the formal representation of interactions between two components in software architectures proposed in ((Allen, 1997; Shaw and Garlan, 1996)) an atomic link is defined with two concepts: glue, the interaction, and the role of each participant in the interaction.

For example, two vehicles can communicate through an atomic underwater communication link. The role defines the commands/messages accepted and issued by each vehicle. The glue defines both the type of the available communications and the state constraints that the vehicles are required to satisfy to communicate (the distance between them should be less than the communication range).

A complex service is a service that cannot be delivered by a single object. This mission example requires two complex services: acoustic navigation and acoustic network.

Acoustic navigation. It is a complex service since it results from the composition of the beacon atomic services provided by at least two buoys. The composition is done in terms of a configuration. A configuration is a list of links connecting a set of entities. For each vehicle, the acoustic navigation service can be provided in several configurations. The set of all of these configurations is described by a configuration style. A configuration style defines properties shared by a set of configurations. In practice, a configuration style defines a disjunction of configurations.

Acoustic network. It is a complex service since it constrains the vehicles and the buoys to satisfy some configurations to implement an underwater communications network. This requirement is expressed as a network configuration style. The messages exchanged follow the interactions defined in the corresponding atomic communication links.

The AUVs implement an optimization-based search algorithm. To do this, they must conform to the conjunction of both the acoustic navigation and acoustic network configuration styles.

From the control point of view, the two configuration styles define, on the one hand, state constraints for the vehicles to satisfy, and, on the other hand, the permissible interactions across the network. The ensemble of entities and the two configuration styles establish both the means and the constraints for the implementation of the algorithm. In turn, the algorithm controls the ensemble.

The above leads to an useful definition of a team. A team is a set of entities linked among them. This is the case of the elements in the two sets Vehicles and Buoys.

The concepts of trajectory or path tracking are no longer adequate to describe this type of mission profile, and to control the system. However, the concept of maneuver lends itself to useful generalizations for specification, control design, and execution. This requires the consideration of the abstractions introduced above: atomic and complex service; atomic link; role and interaction; configuration; configuration style; composition; team; and team maneuver.

The concepts of maneuver specification and control are extended in two ways: 1) single-vehicle maneuvers with links to other maneuvers; 2) team maneuvers. The first type is used primarily for decentralized interactions among vehicles under the control of coordinated mission plans. Each vehicle executes maneuvers from its independent mission plan. In turn, these plans are designed to interact (von Martial, n.d.). The second type models patterns of interactions governed by a centralized controller.

The notions of service, link, configuration, composition, and team proved quite useful to describe this mission and have the potential to model more complex patterns of interactions. For example, services provided by teams, interactions among different teams, etc.

4.2 Control architecture

The extension of the concept of maneuver leads naturally to a convenient extension of the single-vehicle control architecture with the introduction of the team layer on the top of the previous ones. The extension requires three modifications to the previous modules: 1) the vehicle supervisor accepts external links other than those to the plan supervisor; 2) the state of the vehicle includes links to other entities; and 3) the vehicle supervisor includes configuration styles to define the permissible links. In the new architecture, each vehicle supervisor is linked to an operator, to its plan supervisor, or to a team controller. The extended architecture is depicted in figure 4.

The team layer extends some of the concepts of the single-vehicle control architecture. The state of the team includes the constituent vehicles and their current configuration. There is a library of team maneuver controllers. The team supervisor accepts links and team maneuver specifications from an operator, maintains the state of the team, and commands and supervises the execution of team maneuver controllers, one at a time.

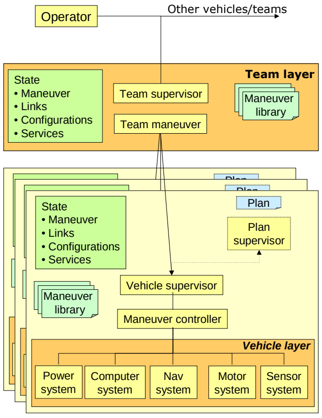

Fig. 4. Control architecture for multi-vehicle operations

The team maneuver controller is a hybrid automaton. It encodes the patterns of control interactions required for the team vehicles to execute a team maneuver. It does this by establishing links to the vehicle supervisors of the vehicles in the team. These links conform to the team configuration style. In practice, those interactions occur in a dynamic network of hybrid automata since the links, and the underlying interactions, may change with time.

The interactions with the vehicle supervisors depend on the type of the corresponding links. Maneuver commands and actuator commands for low and high bandwidth links, respectively. For example, the following interactions may take place to implement the optimization algorithm. Vehicle A measures an abrupt change in the value of the temperature in location R and sends a message with this information to the team supervisor. The team supervisor knows the locations of the team members and commands a selection of them to move to R. It does this by sending single-vehicle maneuver commands of the type *goto R* to each one of these vehicles.

This architecture is fully scalable and, in particular, it allows for the addition of other layers on the top of the ones depicted in figure 4 and for more complex control actions. Example of these control actions are: 1) transferring vehicles among teams; 2) creating and deleting team controllers; 3) moving the physical location of team or vehicle controllers; and 4) establishing additional interactions among teams. In the context of the PISCIS project, these control actions are left to the operator since the architecture implemented is the one depicted in figure 4. In terms of mixed initiative, the operator can intervene at all levels of the architecture by conforming to the link interaction rules.

See ((Milner, 1996; Milner, 1999)) for a formal approach to the problem of mobility and a discussion on the mathematics of linkage in the perspective of Robin Milner.

4.3 Dynamic optimization perspective

It is difficult to accommodate state-based configuration constraints resulting from configuration styles, set-based specifications and control interactions, varying numbers of vehicles, message-based interactions, and algorithmic specifications under a common control framework. But, at least conceptually, dynamic optimization can provide some of the answers.

According to the approach to the control of interacting dynamic systems proposed in ((de Sousa and Pereira, 2002*b*; de Sousa *et al.*, 2002)) there are three essential notions for the control of these systems: 1) invariance of a dynamic system with respect to a set; 2) monotonicity of a dynamic system with respect to a scalar field; and 3) solvability tube for a target set ((de Sousa *et al.*, 2002; Pereira, 2001). The first one gives the conditions under which the trajectories of the dynamic system do not leave the set. The second one gives conditions for the dynamic system to be able to track gradient lines of the scalar field. The third one defines the set of all states from which a target set can be reached by the dynamic system. The first and second notions are easily related to control Lyapounov functions. For a detailed discussion of these topics see the books (Kurzhanskii, 1997; et. al., 1998; Krasovskii and Subbotin, 1988; Aubin and Frankowska, 1990). These notions are easily extended for interacting systems.

Independently of the interactions occurring within the architecture, at the bottom of the hierarchy there are vehicles, whose behavior is described by ordinary differential equations. The set of all states that can be reached by a vehicle is termed the reach set of the vehicle. The participation of a vehicle in any interaction results necessarily in a reduction of the size of the original reach set, since the vehicle controls have to satisfy additional constraints inherent to the interaction. This applies to any type of interactions: antagonistic, asynchronous, under state-constraints, etc.

The concept of value function from dynamic optimization is crucial to establish essential connections among all of those apparently unrelated notions, and also to conceptualize controllers ((Kurzhanskii and Varaiya, 2000; Varaiya, 1998; Kurzhanskii and Varaiya, 2002*a*; Kurzhanskii and Varaiya, 2001)). Consider first the definition of reach set of a dynamic system $\dot{x} = f(t, x, u), u \in U(t)$. Suppose the initial position and time (x_0, t_0) are given.

The reach set $R[\tau, t_0, x_0]$ of the system at time τ, starting at position and time (x_0, t_0) is given by:

$$R[\tau, t_0, x_0] = \bigcup \{x[\tau] | u(s) \in U(s), s \in (t_0, \tau]\} \tag{1}$$

The reach set at time $\tau > t_0$ starting at set X_0 is given by:

$$R[\tau, t_0, X_0] = \bigcup \{R[\tau, t_0, x_0] | x_0 \in X_0\} \tag{2}$$

The key observation is that the reach set is the level set of an appropriate value function ((Kurzhanskii and Varaiya, 2002*b*; Kurzhanskii, 1993; Kurzhanskii, 1997)). The value function gives the optimal value, if it exists, of the performance of the system with respect to some criteria for a given initial state and time. The relation between the reach set $R[\tau, t_0, x_0]$ and a value function is described next:

$$V(\tau, x) = \min_{u(.)} \{d(x(t_0), X_0) | x(\tau) = x\} \tag{3}$$

$d(x(t_0), X_0)$ is the distance, at time t_0, between the state of the system and X_0 for a trajectory starting at x at time τ. Obviously, (τ, x) is in the reach set if this distance is zero. But this also means that the reach set is the zero level set of the value function in equation (3):

$$R[\tau, t_0, X_0] = \{x | V(\tau, x) \leq 0\} \tag{4}$$

5. CONCLUSIONS

It is an exciting decade to work on underwater vehicle systems and technologies. Unmanned underwater vehicles are becoming part of underwater operations in scientific, military, and commercial applications. On the one hand, the successes, and also the failures, of operational deployments lead to new technological requirements, and to new concepts of operation. On the other hand, new technological developments lead scientists, military, and entrepreneurs to envision concepts of operation which could not have been imagined before.

One common topic seems to emerge from all of these concepts: the networked operation of heterogenous air and underwater vehicles, satellites, mobile and fixed sensors, and human operators. These concepts pose new questions and challenges to control engineering, computer science, and telecommunications. New theories and tools are required for control design: to select controls such as actuator inputs, links to other devices, or roles of vehicles; to handle control constraints such as rules for linking vehicles and for allocating vehicles to roles; and to handle control objectives such as the delivery of services in a region, or the implementation of algorithms.

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