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SENSOR SYSTEMS ON NETWORKED VEHICLES

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Abstract. The future role of networked unmanned vehicles in advanced field studies is discussed in light of the recent technological advances and trends. Visions for systems which could have not been designed before are contrasted to the legal, technological and societal challenges facing the deployment of these systems. The discussion is illustrated with examples of developments from the Underwater Systems and Technologies Laboratory (LSTS) from Porto University.

1. **Introduction.** The beginning of the 21st century has been marked by the increasingly sharper perception of the complex challenges that humankind is bound to face in the near future. Climate change, over-exploitation of natural resources, pollution, poor urban management, and degradation of bio-diversity are well known, large scale, anthropogenic phenomena which question the human role and praxis on planet Earth. In order to properly address these challenges, a much better understanding of the various phenomena of interest and an effective assessment of the human footprint are required. The urgent need for a clear understanding of these phenomena constitutes a strong motivation for the scientific and engineering communities to develop novel approaches, systems and technologies for the badly needed field studies of varied types: environmental, climatological, oceanographic, hydrological, etc. In the reminder of the paper we use the words *field studies* to designate all of these types of studies.

The last decades have witnessed unprecedented technological developments in computing, communications, navigation, control, composite materials and power systems, which have led to the design and deployment of the first generations of unmanned vehicle systems. These vehicle systems have seen action at sea, in the air, on the ground and on other planets. Future generations of unmanned vehicle systems will reflect current trends: increased levels of autonomy, lower cost, longer endurance, and networking capabilities. These trends enable scientists and engineers to develop visions for future systems, and applications, that could have not been imagined before.

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Field studies are one of these applications. These are becoming more and more demanding as scientists seek to understand, for example, environmental, climatological, oceanographic and hydrological processes. But this is a challenging task: our environment evolves in multiple temporal and spatial scales as the result of complex interactions which are far from being fully understood.

Data collection is one of the difficulties associated to field studies. Sensors are required to take measurements with adequate temporal and spatial resolutions, and the measurements may have to be communicated in real-time to adapt the sampling strategies (both temporally and spatially) to the observations. In summary, distributed sensing with mobile nodes has to be complemented with communications and real-time decision making. This is why networked vehicle and sensor systems have the potential to revolutionize field studies.

There are several challenges associated to the vision underlying this revolution. The availability of affordable vehicle systems with inter-operable networking capabilities is still far in the future. The same happens with the capability to design and deploy networked vehicle systems in a systematic manner and within an appropriate scientific framework.

The paper discusses the roles of unmanned vehicle systems in future field studies in light of the recent technological developments and trends, with special emphasis on networked vehicle systems. The discussion is illustrated with examples of developments from the Underwater Systems and Technologies Laboratory (LSTS) from Porto University. The LSTS was established in 1997 and involves students and faculty from the Electrical and Computers Engineering, Informatics and Computing Engineering and Mechanical Engineering departments from Porto University. The mission of the LSTS concerns the design, construction and deployment of innovative vehicle/sensor systems for oceanographic, environmental, military and security applications.

The paper is organized as follows. Section 2 presents an overview of the current capabilities and limitations of unmanned vehicle systems. Section 3 examines the potential of networked vehicle systems in future field studies, and discusses the associated technological, societal and legal challenges. Section 4 presents a taxonomy for field studies with autonomous vehicles, with emphasis on underwater vehicles and discusses the state-of-the-art for each of the problems identified in this taxonomy. We briefly discuss how the techniques developed for single-vehicle operations can be extended to multi-vehicle operations under communication constraints. Section 5 presents the LSTS approach to the deployment of networked vehicle systems to illustrate the key points discussed in the paper. Finally, Section 6 presents the concluding remarks and draws the attention to the need to stimulate the development and deployment of networked vehicle systems over the next decades.

Appendix A presents a list of the symbols used throughout this document.

2. **Unmanned vehicles: Trends and technologies.** In the recent past, we have seen the increasing success of unmanned vehicle systems: Autonomous Underwater Vehicles (AUVs) operating under in the Arctic; Unmanned Air Vehicles (UAVs) performing atmospheric research; cars driving autonomously in the desert or in the city; rovers performing data collection on Mars; robots playing soccer; etc. The key to this success comes from the obvious fact that these are unmanned vehicles: they can perform dirty, dull and dangerous tasks in all types of environments (ocean, air, land and space). The operation of unmanned vehicles does not necessarily remove

humans from the operation of the vehicle. In remotely operated (or piloted) vehicles, there is a human operator in charge of piloting the vehicle, which may be operating in some remote location. This is done with the help of a communication channel: sensor information is sent from the vehicle to the operator which, in turn, sends commands to the vehicle. The reliance on the operator and on the communication channel is the main limitation of this mode of operation. This is not compatible with the operation of vehicles in some remote environments, such as the ocean or the space, where communications are typically difficult.

Autonomous vehicles are the (partial) answer to the limitations of remotely operated vehicles. Autonomous vehicles are capable of executing mission plans without the intervention of human operators. There are several degrees of autonomy, some of which are not feasible with the current technology [2]. For example, full autonomy is still not feasible today: vehicles lack the sensing and reasoning capabilities required for that purpose. This is partly why the concept of mixed initiative operation was introduced in the last decade [15]. In this concept, human operators are part of the planning and control loops of the vehicle. Informally, this can be described as "supervised" autonomy. For example, the operator is capable of developing mission plans which can be uploaded to the vehicle for autonomous execution; the operator is also able to override plan execution and to re-task the vehicle to execute new plans.

Depending on the operational environment, key technical specifications for unmanned vehicles include endurance, size, payload, range, communication and navigation capabilities, and deployment mechanisms [4]. Endurance is highly correlated with the limitations of current energy storage technologies. Energy is at premium in unmanned vehicles, especially when these are designed for operation in remote environments. The size of the vehicle typically constrains the payload and energy storage. The payload is what makes the vehicle useful. Payloads normally concern sensors and actuators.

Sensor development is one enabling technology for unmanned vehicles (at the end of this part, in Section 2.1, there is a brief aside on oceanographic sensors). Power and size are the major limitations of the payload. Range depends not only on endurance, but also on the operational environment (e.g., the maximum operating depth is a major design parameter for submarines).

Communication and navigation capabilities determine the level of human intervention, the practical endurance, and the usefulness of the vehicle. The vehicle cannot go beyond the range imposed by limitations of the navigational equipment without becoming lost (e.g., the Global Positioning System (GPS) is not available everywhere). Communications are necessary for operating and retrieving information from the vehicle (the vehicle becomes useless if we cannot communicate with it). Deployment mechanisms determine how easy, and expensive, it is to deploy the vehicle.

There is not a Moore's law for unmanned vehicles. However, from the technological advancements in computation, power storage, sensor technologies and communications, it is possible to infer a few trends for unmanned vehicles: miniaturization (more capabilities in less space), longer endurance and better networking capabilities. Space limitations preclude a thorough discussion of current capabilities and limitations of unmanned vehicle systems. However, these need to be fully understood before unmanned vehicles can be effectively deployed in field studies.

2.1. **Aside on oceanographic sensors.** The evolution of oceanographic sensors has been driven by the need to reduce size and power consumption without reducing capability. A number of sensors that measure biological, chemical, optical, and physical properties in the water column, or gather information about the seafloor, have met these space and energy requirements. Temperature and salinity sensors were among the first, followed by optical and acoustic sensors. These sensors are now commonly used in several autonomous platforms [28]. A brief overview of sensors currently in use on AUVs is provided next.

2.1.1. *Optical Sensors.* The most common oceanographic applications of optics are radiometric measurements in the visible wavebands and individual particle imaging. The small size and modest power consumption of radiometric sensors make them compatible with most AUV platforms. Radiometric sensors can be passive or active; based on whether the light source is independent or part of the system. Passive sensors measure apparent optical properties (upwelling and downwelling radiance, diffuse attenuation coefficient, solar-stimulated fluorescence, and bioluminescence) while active sensors measure inherent optical properties (absorption, scattering, and attenuation coefficients) and fluorescence. Passive sensors consume less power but cannot operate at night or below the photic zone. On the contrary, active sensors have higher consumption but can operate at night, below the photic zone and at wavelengths that have reduced penetration below the ocean surface (such as ultraviolet and infrared), making it possible to detect phenomena such as diel changes in particle concentration, sinking phytoplankton aggregations and detached nepheloid layers. Optical sensors can be used for studying responses of the carbon cycle [6] to climatic changes in mixed layer processes, providing a vertical dimension to surface phytoplankton and other particle fields derived from ocean color imagery obtained by remote sensing (e. g., satellites).

2.1.2. *Physical Sensors.* Temperature probes [38] have been widely used in oceanography and their size enables the integration into the smallest platforms. The Conductivity, Temperature and Depth (CTD) sensor is the primary tool for determining essential physical properties of sea water. In recent years salinity probes have reduced their size, but often it is necessary to pump water through the sensor to attain higher accuracies. The microstructure sensors in current use are fast-responding thermistors and airfoil shear probes. Although these sensors have problems with measuring while moving, both types have been implemented successfully in propeller-driven platforms and the former has been incorporated into autonomous profiling floats. However they are only suitable for speeds less than 1 m/s. A new type of salinity sensor, based on capillary micro-conductivity [19], solves this problem and works at vehicle speeds as high as 4 m/s, making it suitable for propeller driven platforms.

2.1.3. *Acoustic sensors.* Acoustic signals can travel great distances in the ocean and are useful in a wide range of scientific applications. They are also used for underwater wireless communications, including tracking of SOund Fixing and RAnging (RAFOS, backwards) floats [36]. Acoustic sensing systems are either passive or active, depending on whether they only listen or also generate and transmit. Quantitative interpretation of acoustic signals is often a challenge, requiring the use of multiple frequencies to reduce ambiguity. In addition to the strength of the backscattered signal, its Doppler shift is used to measure the velocity and direction of currents. The Acoustic Doppler Current Profiler (ADCP) is used to measure how fast water is moving across an entire water column. Active acoustic sensors can provide high-resolution maps of the seafloor, zooplankton, fish, and the underside of sea ice. The multi-beam echo-sounder is used to obtain detailed maps of the seafloor. Some systems can be used in water as shallow as 10 meters and as deep as 5000 meters.

2.1.4. *Chemical Sensors.* This class of sensors has not yet been routinely deployed on autonomous platforms. There are some exceptions. Commercial Off-The-Shelf (COTS) electrochemical sensor systems for methane have been used on AUVs and ROVs to map methane generated by decomposing methane hydrates on the seafloor. Oxygen electrodes for gas exchange and biological production have been used on gliders and AUVs, and are being incorporated into profiling floats on a demonstrational basis.

2.1.5. *Present and future of oceanographic sensors.* The suite of acoustical, biological, chemical, optical and physical sensors that can be deployed on autonomous vehicles is already remarkable. However, many of these sensors, particularly chemical sensors, are still prototypes and lack the investment necessary to turn them into robust and reliable COTS sensors [44]. Future challenges in sensor design concern: 1) standardized interfaces ("plug and play" capability); 2) sharing basic components (smart sensors); 3) sensor stability and calibration; and 4) molecular sensing. The desire to solve interdisciplinary problems leads to an increased sensor payload (for simultaneous measurement of more variables) and to robust on-board data processing algorithms.

3. **Networked vehicle systems.** Unmanned vehicles have already proved invaluable in oceanographic and environmental field studies by providing levels of spatial-temporal sampling resolution which could have not been attained before. Recent trends show that the levels of spatial-temporal sampling resolutions attained with individual vehicles are now feasible for wider areas through the operation of persistent vehicle networks. Persistent sampling over wide areas has the potential to revolutionize environmental field studies.

3.1. **The power of networking.** Networking is one of the major trends for unmanned vehicle systems; it is also one of the enabling technologies for distributed cooperation (and computation). In the reminder of the paper we use the phrase "networked vehicle systems" to refer to systems where vehicles, sensors and operators interact through (inter-operated) communication networks.

Networked vehicle systems offer new possibilities to the operation of unmanned vehicles [24]. For example, in networked vehicle systems, information and commands are exchanged among multiple vehicles, sensors and operators, and the roles, relative positions, and dependencies of those vehicles and systems change during operations (see Figure 1). These capabilities are essential for operations where the temporal and spatial coordination of vehicles is required, such as in environmental field studies.

We are still far from realizing the potential of networked vehicle systems. Consider the case of an environmental disaster spanning a wide geographical area. Currently, there is no standard to inter-operate vehicles, sensors and communication networks from different vendors/institutions.

Wireless sensor networks [12] are a major technological trend that is already impacting environmental field studies [32]. The developments on miniaturization

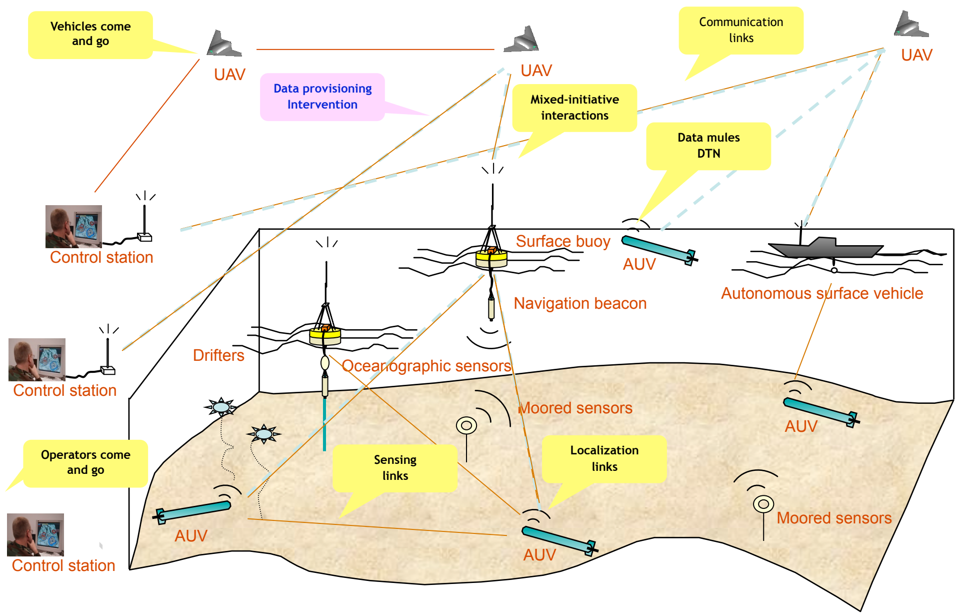

FIGURE 1. Our vision on the networking of sensors and vehicles. Networked vehicle systems imply the establishment of communication links between various types of vehicles, as well as interactions with human operators.

and power consumption will accelerate this trend towards massive deployments, thus enabling studies with unprecedented spatial and temporal resolution. Another promising technological push comes from the inter-operation of vehicle systems and sensor networks which will enable us to get the best of both worlds: area coverage with fixed sensor nodes and adaptation and adjustable resolution provided by sensors mounted on vehicles.

The research community is devoting significant efforts to the development of concepts of operation for networked vehicle systems. Surprisingly, or not, the role of human operators is receiving significant attention in these advances. In fact, this is the reason why researchers and technology developers have introduced the concept of mixed initiative interactions, where planning procedures and execution control must allow intervention by experienced human operators. In part, this is justified by the fact that essential experience and operational insight of these operators cannot be reflected in mathematical models, so the operators must approve or modify the plan and the execution [27, 15]. Also, it is impossible to design (say) vehicle and team controllers that can respond satisfactorily to every possible contingency. In unforeseen situations, these controllers ask the human operators for direction.

The idea of a system of systems seems appropriate to capture the essential aspects of operation of networked vehicle systems. The observation is that the components in the network are part of a system within which new properties arise, some as planned, some emergent. 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, in the sense of migrating from one computer to another one (as part of the evolution of the system).

This poses challenges to robotics, control, computer and communication scientists. 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. These advances can only be achieved by adopting an inherently interdisciplinary approach, bringing together researchers from traditionally separate communities to work on problems at the forefront of science and technology.

3.2. **Field studies.** Despite the advances described in the previous sections, we are still far from being able to design and deploy networked vehicle systems for field studies in a systematic manner, and within an appropriate scientific framework. This requires a significant expansion of the basic tool sets from each area, and the introduction of new techniques that extend and complement the state of the art. Because such developments call for an interdisciplinary approach, in what follows, we only describe trends, without advocating specific concepts for field studies.

Currently, there is a worldwide trend for the development of ocean observatories [13]. This is a good example of large scale persistent data sampling, with adjustable sampling resolutions. It involves of a wide range of mobile platforms including drifters, AUVs and ships, fixed measurement assets such as moorings and radar, and remote measurements from satellites and aircrafts. Moreover, the components of an ocean observatory system are reconfigurable to respond to observational opportunities and changing objectives.

Communications are a major challenge for ocean observation systems. These systems include intermittent inter-operated networks. Often deployed in dynamic and extreme environments lacking continuous connectivity, many such networks have their own specialized protocols, and do not utilize the Internet Protocol (IP). Delay-Tolerant Networking (DTN) is one approach to address this problem. DTN is a network architecture and application interface structured around optionally-reliable asynchronous message forwarding, with limited expectations of end-to-end connectivity and node resources. For example, this enables vehicles to perform the role of data mules to move data between places which are not physically connected.

Energy storage and transmission is another major challenge. Cabled observatories have been proposed to address this challenge. The cost of this approach is the motivation behind the development of other energy sources for ocean observatories.

In most concepts for ocean observatories, sampling is achieved with the help of both fixed and mobile sensors. This aims at combining the best of both Eulerian and Lagrangian approaches to the problem of studying fluid properties [44]. The terms Eulerian and Lagrangian refer to different frames of reference for studying these properties: Eulerian frames of reference are fixed in space and time; Lagrangian frames of reference move with the fluid. Moorings are the most common Eulerian platforms in oceanography. Unmanned Underwater Vehicles (UUVs) and drifters are Lagrangian platforms. This classification is not strict since moorings may move with the flow – in a limited fashion – and vehicles can move independently of the fluid flow.

The problems of real-time oceanographic field studies are examined in [47], where adaptive sampling and aliasing are discussed, and conditions under which energy efficient sampling can take place are presented. The problem of mapping an ocean front with AUVs is discussed in [45]. The problem of gradient descent based on point-wise measurements taken by multiple vehicles is discussed in, e.g., [41]. Terrain mapping strategies for AUVs are discussed in [46].

The experience gained with trials like the Monterey Bay 2006 field experiments (MB06) may help the community to understand the operation of ocean observatories. MB06 took place over a two-month period from mid-July through mid-September 2006, and involved over a dozen different institutions, thirteen research vessels, over three dozen robot submarines, and many other fixed and drifting oceanographic instruments. The scale of the experiments is explained by the uneven seafloor and constantly changing currents in the Monterey Bay. These experiments examined coastal ocean processes from different perspectives, and at unprecedented different physical scales. These took place on a 24/7 base. The Collaborative Ocean Observatory Portal was developed to support the day-to-day participation of the large group of researchers with ties to geographically diverse institutions throughout North America. These investigators had to interact on a continual basis to optimize data collection and analysis [25].

Persistent large scale observation is not specific to the oceans. The oceans represent an extreme environment where technical challenges are exacerbated (e.g. GPS and radio communications do not work underwater), thus providing guidelines for deployments in other environments. In some environments, the deployment of new sensors and vehicles will complement existing sensing systems. This may be the case with environmental sensors for some major cities. It is not uncommon for different organizations to own environmental sensors distributed over these cities. However, the assimilation of the data provided by all of these sensors is less common. The assimilation of this data has a significant potential for environmental field studies. However, several difficulties must be faced before this data can be used. First, data has to be available. Second, it must be available on the right formats. Third, it has to be reliable (sensors have to be calibrated). Security, levels of access, availability on a need to know basis, and models of operation represent other difficulties. This means that, in addition to the technical difficulties, there are some organizational, cultural and political difficulties. The technical difficulties are not insurmountable, and the cost of networking does not seem to be a major issue.

Networking existing sensors has the potential to add value to the existing infrastructure. This value can be further increased with networked vehicle systems. Cities are one example where this idea can be easily applied. Different institutions (high schools, universities, companies, municipalities, etc.) have been using environmental sensors on their daily activities. The Internet is now pervasive, and connecting these sensors to the Internet is not a major technical problem. In fact, permanent connectivity is not needed. City transportation vehicles can be instrumented with sensors for area coverage. DTN technology allows the data collected along each route to be automatically stored on each vehicle and later forwarded to some Internet server when short range (i.e., low cost) communications are available. Citizens can also contribute sensor measurements from either their mobile phones or from sensors connected to their home computers. This may lead to a sensing system of unprecedented dimension and capability, which has applications not only in environmental field studies, but also in civil protection and improving the quality of city life. The new sensing system will have certainly new properties, which cannot be fully anticipated now. This model can be easily replicated; it may be a first step towards the instrumentation of the Earth.

3.3. **Challenges.** There are several obstacles in the road to the practical – as opposed to experimental – deployment of networked vehicle systems. These are briefly discussed next.

Currently, there are no legal frameworks to encompass the operation of unmanned vehicles. In most countries the operation of air vehicles in controlled air space is severely restricted. Efforts are underway to address this problem in some European countries and in the United States of America. The operation of unmanned ocean-going vehicles also presents legal challenges. The Society for Underwater Technology published a recommended code of practice [10] and reports on this topic since the last decade [8]. But this is not the United Nations' Law of the Sea, where issues such as the responsibility for collisions and the property of vehicles found at sea are resolved in the context of the rules applicable to piloted vehicles. This legal void precludes practical deployments with ocean-going vehicles. Each deployment is the exception, and not the rule.

The lack of standards for inter-operability is preventing researchers to operate, in a transparent manner, vehicles from different vendors in the same network environment. The lack of standards is not unique to inter-operability. Currently there is no standardization in the area of underwater communications, to name just one example. There are several initiatives addressing these issues. NATO has been working on standards for inter-operability, namely the STANAG 4586 [39], which has seen some acceptance in the UAV community; this is confirmed by the existence of commercial software products compliant with this standard. The Joint Architecture for Unmanned Systems (JAUS) is receiving wide acceptance in the military, especially in the USA. The NATO Undersea Research Center in La Spezia is developing the JANUS standard that will allow acoustic modems to coexist, advertise their presence and potentially inter-operate. A word of caution is needed here: the existence of standards does not imply standardization.

In general, commercial vehicles have not been developed as open systems. Moreover, the lack of standards for inter-operability is not conducive to open systems. Closed systems tend to raise vehicle and maintenance costs, and may be conducive to forms of market practice that are not necessarily in the benefit of the customer. This is especially critical in a field where technological obsolescence arises rapidly: vehicles and their components have to be upgraded periodically. Some technological trends, namely those related to miniaturization and embedded systems, may contribute to change this state of affairs by reducing the cost of these systems. Low cost open systems may prove fundamental to the dissemination of networked vehicle systems.

This state of affairs should not prevent us from deploying unmanned vehicle systems. On the contrary, we are learning important lessons from our deployments [35]. These may prove invaluable for the development of legal frameworks, standards and concepts of operation.

4. **Active sensing techniques for unmanned vehicles.** Unmanned vehicles are one of the key enabling technologies for characterizing spatially and temporally distributed phenomena. The problem is that the spatial and temporal scales of most phenomena of interest preclude exhaustive sampling, i.e., it is not feasible to sample the whole region where the phenomena occurs in a timely fashion. Hence, we are required to endow the vehicles with the capability to improve their sampling efficiency. One way to do this is to use the samples already taken to adapt the sampling strategy. Another way is to coordinate the sampling strategies of several vehicles. In both cases, we are talking about *active sensing* – or *sensor-based* – techniques.

By active sensing we mean that we will use sensor readings as an input to some algorithm (or technique) that attempts to solve our some sensing problem. Sensors play therefore an essential role on the problem that we discuss, but they are not the only concern. There are many constraints and possibilities that arise whenever we design a solution to active sensing problems for unmanned vehicles, e.g., motion, communication and energy consumption.

AUVs enable the examination of several hydrographic and oceanic features at a close range, at a relatively low cost and with reasonable accuracy. The purpose of this section is to present an overview of active sensing problems and techniques for this type of vehicles. We are particularly interested in techniques for multi-vehicle systems, and how these compare to single-vehicle techniques.

The discussion is about problems and techniques for AUVs only, but some issues and solutions are applicable to other kinds of autonomous vehicles.

Basic definitions. Before proceeding any further, we introduce some definitions that will be used throughout this document. They are general definitions of basic elements of active sensing problems and techniques.

- **Field.** A field consists of a map $\mathcal{F} : \mathbb{R}^n \mapsto \mathbb{R}^m$, which can be time-varying or static. The values of n concern the spatial (2D or 3D) and temporal dimensions; m is typically 1 thus indicating a scalar field. Most problems assume scalar fields, but generalizations are often possible and sometimes investigated. An example field ($\mathcal{F} : \mathbb{R}^2 \mapsto \mathbb{R}$) is a seabed altitude profile.
- **Operating area.** The area on which we are interested in testing our solution to a problem is called the operating area $\mathcal{A}$. It is defined in $\mathbb{R}^2$ or $\mathbb{R}^3$ and usually rectangular. The operating area sets the limits for the operation of our vehicles, which would otherwise be constrained by the available energy. Therefore, the field $\mathcal{F}$ may not need to be defined outside $\mathcal{A}$.
- **Vehicles.** Our vehicles, AUVs, are defined as a set $V = \{v_1, ..., v_N\}, N \geq 1$. They typically have motion, communication and sensing capabilities and limitations.
- **Sensors.** Sensing capabilities in AUVs are enabled by the mounting of sensors. Each sensor is capable of taking measurements of a quantity with a given accuracy and frequency. The quantity a sensor measures is a function of value of the field $\mathcal{F}$ (if scalar valued) or of one of its components (if vector valued).

4.1. **Active sensing problems for AUVs.** We organize active sensing problems for AUVs into four types. For each type, we provide a general mathematical formulation and discuss various examples. We then identify activities that are common to different types, and propose a classification of active sensing problems in Section 4.1.3.

4.1.1. *Types of problems.* This section describes the types of problems we identified. We explain their formulations, relying on the basic definitions outlined previously. Every formulation assumes *a field $\mathcal{F}$, an operating area $\mathcal{A}$ (or some area interior to $\mathcal{A}$) and the use a set V of AUVs equipped with sensors, adequate to the quantity(ies) of interest.* The examples given are not exhaustive, but intended to be representative.

Search for extrema. This type entails finding global or local extrema values of the field $\mathcal{F}$. Typically no a priori knowledge of the field $\mathcal{F}$ is assumed. Then, these problems can generally be formulated as

Problem 4.1 (Search for extrema)**.** *Find the minimum (or maximum) values of $\mathcal{F}$ according to some norm in $\mathbb{R}^m$, with the highest possible accuracy.*

Search for extrema arises, for example, in the problems of computing the depth of a pond [9], locating cold spots [16] or finding hydrothermal vents through temperature sampling [3, 9]. It poses many questions in the sense that it is hard to optimize the vehicles' computational and motion efforts, while keeping the search fast and accurate.

Source Localization. When the field $\mathcal{F}$ is modeled as being originated from one or more points in space, we might be interested in localizing those points or sources. Source localization problems usually include the tracking of the field according to some law so that the source is gradually approached.

When considering problems of this type, the field is usually assumed to be described by some model. For example, plumes can be modeled using partial differential equations perturbed by some noise. These models are useful in deriving approaches to source localization problems. Their formulation can be stated as

Problem 4.2 (Source Localization)**.** *Let the field $\mathcal{F}$ be described by some model and originated from one or more source points. Find the location of the source(s), with maximum accuracy.*

Finding sources is one of the goals of Chemical Plume Tracing (CPT). CPT is a problem that can described as following a plume, characterized by the concentration of a chemical substance, down to its source [29, 42]. Another example is the prospecting of hydrothermal vents [29].

Survey. A survey entails the collection of sensor readings over the operating area $\mathcal{A}$ so that a map of the field $\mathcal{F}$ can be generated. The map can then be used for other purposes such as model validation and mission re-planning (adaptive sampling).

In surveys, no *a priori* knowledge of the field $\mathcal{F}$ is typically assumed. Even though the end use of the maps generated through surveying varies, the goal is generally to minimize the sampling errors. It is then necessary to construct sampling schemes, i.e., laws that define *where* and *when* to sample. Then, these problems can generally be formulated as

Problem 4.3 (Survey)**.** *Find surveying algorithms (including motion patterns and sampling schemes) that minimize field reconstruction error.*

There are many examples of surveying problems [47, 20]. Surveys with adaptive sampling are described in [30] and algorithms for uses such as bathymetry are shown in [48].

Feature following. A feature is a distinguishable set of values for the field $\mathcal{F}$, possibly spread over the operating area $\mathcal{A}$, that we would like to detect and track. It is common, in feature-based approaches, to assume no prior knowledge of the field $\mathcal{F}$, but to consider some model of the feature of interest. This model can simply be a scalar (level curves) or a more intricate description of a more complex feature. The problem formulation is, in general

Problem 4.4 (Feature following)**.** *Given a description of a feature to track, find algorithms so that the vehicle(s) follow the feature with minimal tracking error.*

Examples of features include contours (or level curves) and boundaries. Following of level curves is described in [49] and an adaptive approach is shown in [5].

4.1.2. *Activities.* Having described some types of active sensing problems, we now define activities, i.e., the global functionalities required on AUVs. These definitions will enable the classification of the types of active sensing problems in a systematic and informative way.

We consider three main activities: *finding*, *mapping* and *tracking*. Some activities may be common to more than one type of problems. This means that some problems involve a combination of functionalities.

- **Finding.** The first activity entails the pinpointing of a location where some condition regarding the field $\mathcal{F}$ is met. By pinpointing a location we mean the computation of the most likely coordinates in $\mathbb{R}^n$. The condition to be met is usually the observation of some feature (defined in Section 4.1.1) or based on it.
- **Mapping.** This activity consists on the creation of a map, i.e., a representation of the field $\mathcal{F}$ over the operating area $\mathcal{A}$ or some area within it.
- **Tracking.** Roughly speaking, tracking activity is equivalent to finding, but in a dynamic and iterative way. We distinguish it from finding because problems of finding typically differ enough, in terms of objective, from tracking. Take, for example, the different goals of extrema search and contour following.

4.1.3. *Classification.* Using the activities defined in Section 4.1.2, we propose a classification scheme for active sensing problems for AUVs. It is shown in Figure 2.

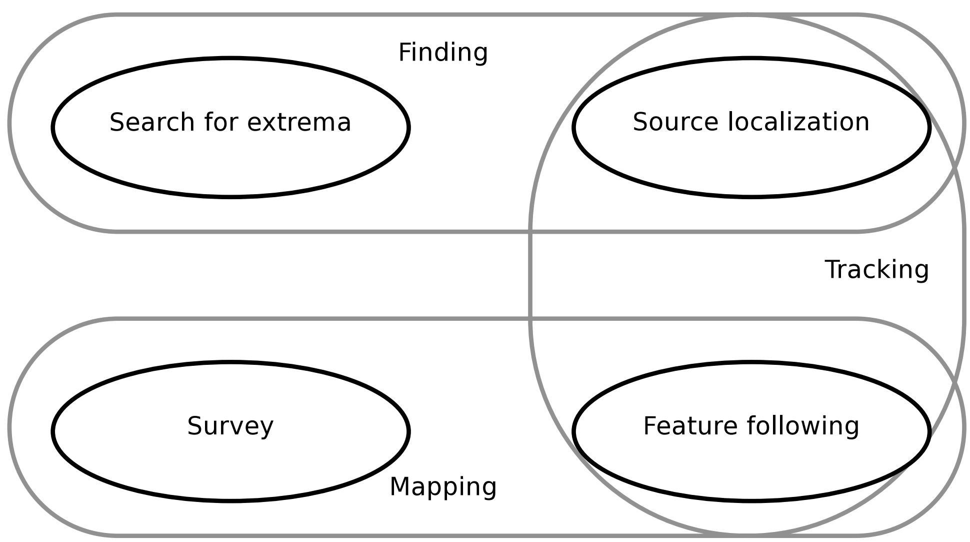

FIGURE 2. A tentative classification for active sensing problems for AUVs. Problems are categorized in types (dark ellipses) and then associated with activities (light shapes). Problem types can entail more than one activity and an activity might be part of various problem types.

This classification scheme is a way to structure active sensing problems. Note that it is not unique and exhaustive in the sense that it might be possible to define other problem types and/or activities. Nevertheless, we believe that it is an adequate and revealing way to present an overview of active sensing problems for AUVs.

4.2. **Limitations.** Many issues and constraints arise when attempting to use any technique to solve a active sensing problem. Before proceeding to a discussion of techniques, we describe some issues related to sampling as well as with the current technology.

4.2.1. *Sampling issues.* In [47], interesting considerations on sampling issues are made. The authors first derive curves that represent the limits for the operation of an AUV while performing surveys. These limits concern both the available energy and the speeds allowed and depend, among others, on the spatial resolution of the grid that divides the operating area and the time given for survey completion. Moreover, they define performance metrics based on spatial and temporal sampling errors in surveys. Using the energy and speed limits, we can then obtain the best feasible performance for a survey.

In general, when tackling an active sensing problem, there are tradeoffs between various AUV parameters and the attainable performance. The work presented in [47] is representative of exactly that. It shows that there are issues with sampling, such as aliasing, that constrain the performance of AUV techniques. Nevertheless, improvements are possible with more or less effort and expenses. One interesting conclusion of [47] is that changing design parameters (e.g. speed, efficiency, etc.) is not as effective at improving performance as it is to use multiple vehicles.

4.2.2. *Technological constraints.* Apart from sampling related issues, there are limitations on the technology behind AUVs. We focus on communication related issues but we also briefly discuss motion and sensing.

Communication. Underwater networks differ largely from terrestrial ones. To see this, note that radio waves are very attenuated in salt water [43]. Therefore, the use of radio communication is quite limited. The usual choice is acoustic communications.

Nevertheless, using acoustic communication brings many drawbacks. These include low bandwidth, high propagation delays, interference and more [43]. As an example, consider two underwater vehicles at a distance of 1500 m. Using acoustic communication, the maximum bandwidth obtainable is about 26.7 kbps and the propagation delay is 1 s (see [43, Sec. 3.1]). For control applications with hard timing requirements, these values are very unfavorable. Furthermore, in acoustic communication, the fact that transmission power is much higher than reception power calls for adaptation of protocols (which are often optimized for terrestrial applications).

Techniques which use underwater communication must then be carefully designed to balance all these issues. Moreover, we can be faced with choices between increasing motion or communication efforts. For instance, in some cases it may be preferable for AUVs to surface to communicate via radio; in other cases it may be better to use slow acoustic communications without surfacing.

Motion and Sensing. AUVs may be designed to be as fast and light as possible, but their size frequently carries additional difficulties. Typically, their turning radius will not allow every desired trajectory. The speed of an AUV will also be limited mechanically and by the available battery capacity. Moreover, when sending motion commands to an AUV, we ought to pay attention to the issue of self-localization.

The ability of a vehicle to localize itself under uncertainty, while keeping track of the surroundings, is the main concern of Simultaneous Localization and Mapping (SLAM). The SLAM problem has had many recent developments; in AUVs, there have been some applications of these developments (see, for example, [40]).

Being our problems and techniques based on sensors, we should definitely address their inherent uncertainty. Every sensor has a certain degree of accuracy, dynamic range, repeatability and more that an algorithm should take into account.

4.3. **Active sensing techniques for AUVs.** Many solutions to the problems classified in Section 4.1 have been proposed. In this section we describe some techniques developed as solutions to active sensing problems.

For each technique we describe their main idea and applicability, i.e., the type of problems each technique was developed for and other uses it can have. We then discuss if and which models are assumed in the development of the technique. Next, the technical approach is analyzed and main results are summarized. We also comment on advantages and disadvantages of the technique under discussion, in general or in comparison to others. Finally, multiple vehicles issues are addressed.

4.3.1. *Gradient based.* The first technique we consider is based on the use of gradients. A gradient provides an indication of how a field evolves in space and can therefore be used as a technique to search for extrema. In general, there exist two methods that make use of gradients: direct gradient estimation and alternative ones.

Direct gradient estimation methods explicitly compute the gradient with the final goal of finding something, usually an extremum. Vehicles are then provided with a direction to follow (the gradient). Some references using this technique are [3, 9].

Alternative methods to direct gradient estimation use algorithms such as simplex, simulated annealing or tabu search [9, 16]. These methods do not require the explicit computation of the gradient.

Models. No a priori knowledge of the field $\mathcal{F}$ is usually assumed.

Technical approach. The approach with direct gradient estimation is usually split in two parts: approximating the gradient and defining motion patterns for the vehicles given a gradient. Gradient approximations can be more or less accurate, and computationally intensive. They can be derived in various ways, e.g., regression or finite differences. Moreover, it is imperative to choose how to instruct vehicles to move, so that a faster search with accurate results can be obtained. For example, in [9], direct gradient following is compared to a circle search method. The latter is shown to perform better than the former.

For the alternative methods, the underlying algorithm usually specifies vehicle's motion patterns without much effort. Take, for example, the case of the simplex algorithm, as described in [16]. With some modifications, the simplex algorithm easily provides waypoints for the vehicles to move to.

Results. A comparison of results for gradient based methods is presented in [9], for a single vehicle. Direct gradient estimation is effective and fast when alternative motion patterns are considered (circle search method). When directly following the gradient, effectiveness is lower than for simulated annealing, though speed is greater.

Advantages/disadvantages. Directly estimating a gradient in a field $\mathcal{F}$ can be problematic if the field is not smooth or if there are many local extrema. Moreover, it is often computationally demanding and it requires the careful selection of paths (or motion patterns) in order to maximize the quality of the gradient estimate with respect to the motion effort.

The alternative methods that do not require the explicit computation of the gradient are more robust and computationally lighter. They can also be proven more effective in searching for extrema.

Multiple vehicles. Although the gradient based methods work well for single vehicles, the largest improve in performance comes, in principle, from using multiple vehicles.

But when using multiple vehicles, it is necessary to coordinate their action (motion and communication) in order to optimize the search procedure. This is typically more complex than defining motion patterns for single vehicle approaches. Examples of schemes include layered control with a master-slave communication protocol [16] and virtual bodies/artificial potentials [3]. These examples show promising results for the deployment of gradient based approaches with multiple vehicles. Robustness and effectiveness is added in comparison with single vehicle approaches, as well as tolerance to failures (from redundancy).

4.3.2. *Probabilistic and behavioral methods.* Other methods rely on probabilistic and behavioral tools. These provide the means to deal with the uncertainty in the environment a vehicle is inserted in. Applications include source localization [21, 22, 42] and feature following [5].

We consider two probabilistic approaches: Hidden Markov Methods [21] and Bayesian inference [42]. These methods provide mapping and localization capabilities that enable source localization.

Behavioral robotics [7] provides a framework for building intelligent systems through the use of independent modules (behaviors). It enables reactive systems as opposed to planning-based systems, thus being able to cope with harsher, more uncertain and complex environments. Applications have been found in both source localization [22] and feature following [5].

Models. For these methods, usually a model of the field is assumed. For instance, in CPT, partial differential equations can be used (see Section 4.1.1). If we have a problem of feature following, then a model of the feature is necessary (see Section 4.1.1).

Technical approach. The approach for these kinds of problems depends on the particular method employed. For example, when using Bayesian inference to perform CPT [42], a way to compute a source probability map is derived. On the other hand, developing behavioral methods consists mainly in the definition of several, basic modules (behaviors) that will perform the tasks necessary for the application.

Results. For CPT, Bayesian inference has been shown to perform better than Hidden Markov Methods [42]. An alternative approach, using behavioral methods, has been proven effective [22]. Behavioral methods have also been used with success in feature following [5]. These are all very interesting results; however, they are all single vehicle approaches.

Advantages/disadvantages. Probabilistic approaches provide robustness against uncertainties in the environment but can, however, be computationally intensive. Behavioral methods are specially efficient but they require extra simulation efforts before any AUV mission takes place [22].

Multiple vehicles. All the references provided so far for probabilistic and behavioral techniques for AUVs are designed for a single vehicle. We are not aware of any extension to multiple AUVs. Considering the case of CPT, underwater communication restrictions are given as the reasons for unsatisfactory algorithm performance thus the lack of pursuit of multiple vehicles extensions [37, Sec. 6].

4.3.3. *Adaptive sampling.* By adaptive sampling, we mean that we would like to take samples of a field and then perform analyzes on the data collected so that we can rethink our goals. This technique finds applicability in feature following [49] and surveys [30].

Models. No a priori knowledge of the field $\mathcal{F}$ is usually assumed, except if we are using adaptive sampling for model validation or feature following. In these cases, models are usually used to define error metrics or to describe the feature to track, respectively.

Technical approach. To begin with, a sampling metric is usually derived. There is then the need to find motion patterns sampling schemes (described in Section 4.1.1 that minimize this metric.

Results. Promising results, i.e., good performance, for adaptive sampling techniques are reported in [30]. For tracking of level curves, related with adaptive sampling, small errors are reported in the work presented in [49].

Advantages/disadvantages. The adaptive nature of this technique provides a high degree of flexibility. On the other hand, it might not be trivial to find optimal operating points that minimize sampling metrics.

Multiple vehicles. In Section 4.2.1, we noted that using multiple vehicles, in surveys, enables performance improvements greater than changing single vehicle design parameters. Indeed, surveys with adaptive sampling have been developed for multiple vehicles with success, using, for example, virtual bodies/artificial potentials [30].

5. **The LSTS approach.** Although we have discussed technological trends for unmanned vehicle systems in Section 2, the future prospects of networked vehicle systems in Section 3 and looked at many active sensing problems and techniques for AUVs in Section 4, we have still not delved into development and implementation details. This section briefly presents the LSTS approach to the design, construction and deployment of sensors on networked vehicles to illustrate some of the key points discussed in the paper.

FIGURE 3. LSTS vehicles (see text for details).

5.1. **Vehicles.** Next, we briefly describe the ocean- and air- going unmanned vehicles from the LSTS (see Figure 3).

IES is a modified Phantom 500 ROV model from Deep Ocean Engineering [26]. The innovations include on-board power and computer systems (to minimize the number of wires in the tether cable), tele-operation and tele-programming modes and an integrated navigation system which fuses data from an external acoustic system and internal navigation sensors. The inspection package includes a video camera (Inspector, zoom 12:1) mounted on a pan and tilt unit (Imenco) and 600 W of light sources (DSP&L). The navigation package includes a Doppler Velocity Log (Argonaut/Sontek), an Inertial Unit (HG1700 /Honeywell), a Digital Compass (TCM2/PNI) and acoustic beacons (20-30 KHz).

KOS is a modular ROV for underwater inspection and intervention which comes in three basic configurations [27]. It is made of composite materials to reduce weight and for added performance. It has advanced thrust and power control for operations in difficult environments. The dimensions are 120 cm x 70 cm x 90 cm and the weight is 90 kg. It has 5 Seaeye SI-MCT01 thrusters, a maximum operating depth of 200 m and power consumption of 3 KW. It has the same inspection and navigation packages installed on the *IES* ROV plus a 2-degree of freedom robotic arm for interventions.

Swordfish is a 4.5 m long Autonomous Surface Vehicle (ASV) based on an ocean-going catamaran (200 kg) equipped with two Seaeye SI-MCT01 thrusters and a docking station for AUVs. *Swordfish* is a powerful communications node with Wi-Fi and broadband radios, Global System for Mobile communications (GSM) capability and a Benthos acoustic modem for underwater communications [23]. The standard payload includes a wireless video camera and a distributed meteorological station based on a Mote sensor network. It is used both as a gateway buoy for underwater communications, and as docking station for autonomous underwater vehicles. Energy is provided by batteries which can power *Swordfish* for up to 10 hours of operation. It has a GPS unit and a miniature Inertial Motion Unit (IMU) for navigation.

Isurus is a modified version of a REMUS (Remote Environment Measuring UnitS) class AUV, built by the Woods Hole Oceanographic Institution (MA, USA), for low cost and lightweight operations in coastal waters. *Isurus* has a torpedo shaped hull about 1.6 meters long, with a diameter of 20 cm and weighting about 35 kg in air. The maximum forward speed is 4 knots, being the best energy efficiency achieved at about 2 knots. At this speed, *Isurus* is capable of operating for about 12 hours. The maximum operating depth is 200 m. For navigation, *Isurus* uses a PNI TCM2 digital compass and Long BaseLine (LBL) acoustic beacons (20-30 KHz). In the standard configuration, *Isurus* is equipped with an Ocean Sensors 200 CTD sensor, a Wet Labs optical backscatter sensor, a Marine Sonics side scan sonar and an Imagenex altimeter. The communications suite includes a Benthos acoustic modem and Wi-Fi [11].

Our most recent AUV, the *Light Autonomous Underwater Vehicle* (*LAUV*) is a prototype of a low-cost submarine for oceanographic and environmental surveys [31]. It is a torpedo shaped vehicle made of composite materials (110 cm x 16 cm) with one propeller and 3 (or 4) control fins. The *LAUV* has an advanced miniaturized computer system running modular controllers on a real-time Linux kernel. It is configurable for multiple operation profiles and sensor configurations. In the standard configuration, it comes with a low-cost inertial motion unit, a depth sensor, a LBL system for navigation, GPS, GSM and Wi-Fi. The maximum operating time is 8 hours.

Lusitânia is an UAV based on a remotely controlled model airframe equipped with one OS 91-FX, 15 cc, 2.9 HP, 2 stroke engine. *Lusitânia* is equipped with a Piccolo autopilot, a small video camera and Telos motes (with meteorological sensors optimized for use on an UAV platform). The camera can be remotely controlled and provides the operator with a video feed in real-time. This is done through a 2.4 GHz wireless transmission system with a range of 8 Km [1]. Flights are limited to 80 minutes in duration.

ANTEX is a family of UAV platforms developed by the Portuguese Air Force Academy. *ANTEX-X03* is a 6 m wingspan platform with a 220 cc, 22 HP, 2 stroke engine for a payload weight exceeding 30 kg. *ANTEX X02* is a 1:2 scale model of *ANTEX-X03* with a 15 cc, 2 HP, 4 stroke Saito100 engine, for a maximum payload takeoff weight of 7 Kg. The *ANTEX* UAV family has a standard computational and sensor configuration. It is configured to fly with two different autopilots: Piccolo and MicroPilot. The maximum flight time ranges from 1 to 12 hours, depending on the platform and on its configuration.

In addition to autonomous vehicles, we have been developing drifters to monitor ocean currents. In their simplest version, our drifters consist of a simple computer system and a GPS/GSM board installed on a waterproof ocean-resistant container.

The position of the drifter is monitored in real-time with the help of GSM/GPS communications.

5.2. **Planning, command and control framework.** The LSTS has a layered approach to planning and execution control. This approach decomposes a complex design problem into a number of more manageable sub-problems that are addressed in separate layers, which can be verified in a modular fashion. This leads to the modular verification of the framework [16]. We use the concept of maneuver – a prototype of an action/motion description for a vehicle – as the atomic component of all execution concepts. We abstract each vehicle as a provider of maneuvers and services. A simple protocol based on an abstract vehicle interface governs the interactions between the vehicle and an external controller: the external controller sends a maneuver command to the vehicle; the vehicle either accepts the command and executes the maneuver, or does not accept the command and sends an error message to the controller; the vehicle sends a done message or an error message to the controller, depending on whether the maneuver terminates successfully or fails. This protocol facilitates inter-operability with other platforms. Actually, the same protocol is used on-board each vehicle for autonomous execution control [1].

Our control architecture, depicted in Figure 4, consists of two main layers: multi-vehicle control and vehicle control. Each layer, in turn, is further decomposed into other layers. The vehicle control architecture is standard for all vehicles. The multi-vehicle control structure is mission dependent. We use our vehicle abstractions in multi-vehicle controllers that may reside in remote locations or in other vehicles. This leads to different control configurations and strategies.

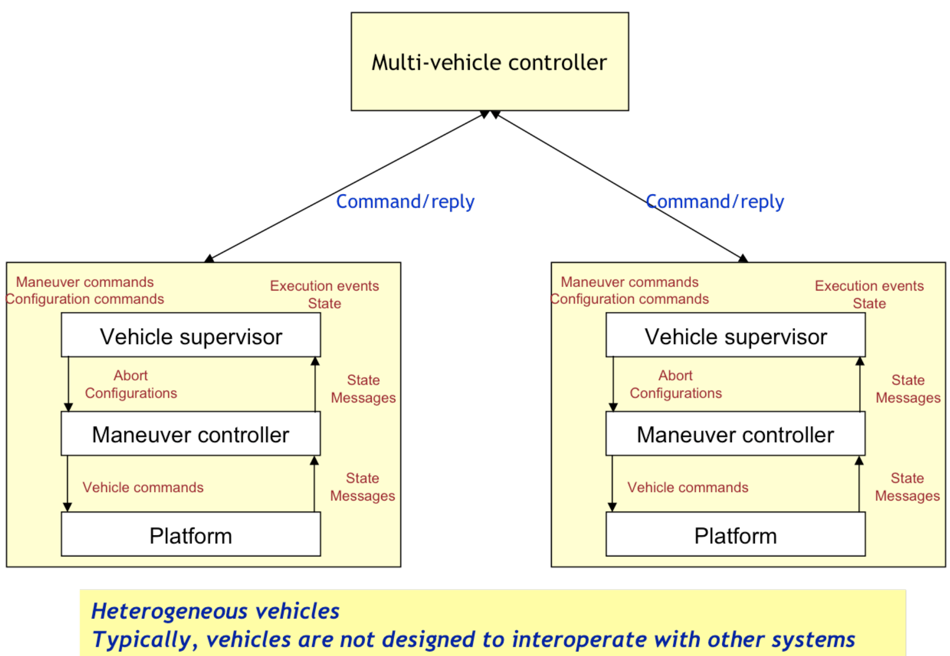

FIGURE 4. LSTS layered control architecture. The vehicle control part of this architecture is used in all LSTS vehicles, which provides an abstraction for the multi-vehicle control part to make use of.

The vehicle control architecture, shown in Figure 5, consists of four layers: low-level control, maneuver control, vehicle supervision and plan supervision.

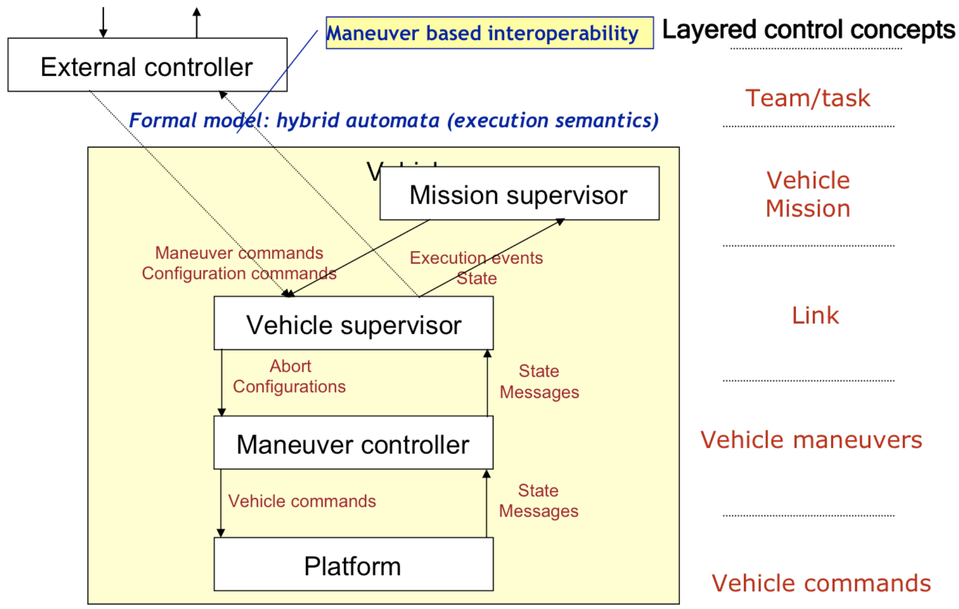

FIGURE 5. LSTS vehicle control architecture. The vehicle control architecture is divided into four layers (as shown), which enables a high degree of flexibility.

The vehicle supervisor controls all of the onboard activities and mediates the interactions between an external multi-vehicle controller (or the internal mission supervisor) and the maneuver controllers. This supervisor accepts maneuver commands (or commands to abort the current maneuver), passes the maneuver parameters to the corresponding maneuver controller for execution, and signals back the completion or failure of the maneuver.

The plan supervisor commands and controls the execution of the mission plan. The mission plan is encoded as a transition structure (see Figure 6). The nodes consist of maneuvers, and the arcs encode the transition logic. 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 mission plan has provisions for mixed initiative control by allowing the operator to enable and disable some of the transitions. The concept of maneuver plays a central role in this 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 is a key element in modular design, since it defines clear interfaces to other control elements. We allow the operator to interact with the execution of some maneuvers. There is a library of maneuvers/maneuver controllers. Example maneuvers include: *Hover, Follow-Trajectory, Surface, Goto, Rows and Tele-operation*. The addition and deletion of a maneuver to the library does not require changes to the control architecture [14].

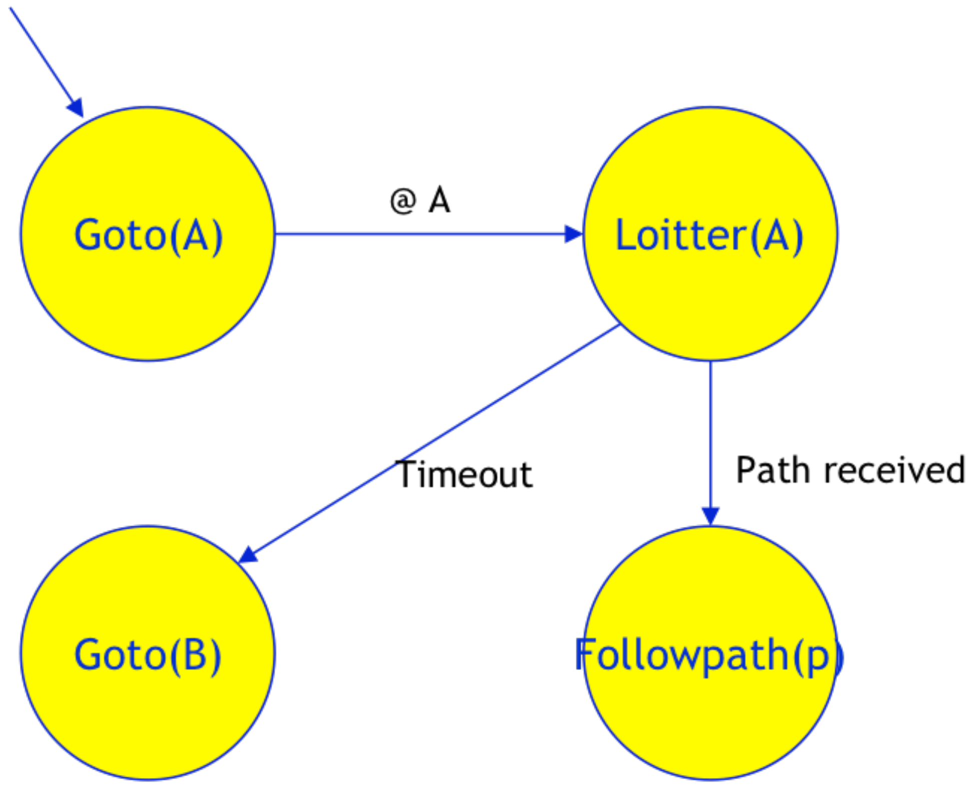

FIGURE 6. Example of mission specification.

5.3. **Software tool set.** We use the *Neptus/Seaware/Dune* tool set, developed at the LSTS, to support the implementation of our planning, command and control framework.

Neptus is a distributed command, control, communications and intelligence framework for operations with networked vehicle systems and human operators [17, 18]. *Neptus* supports all the phases of a mission life cycle: world representation; planning; simulation; execution and post-mission analysis. *Neptus* supports concurrent operations: vehicles, operators, and operator consoles come and go; operators are able to plan and supervise missions concurrently. Additional consoles can be built and installed on the fly to display mission related data over a network. *Neptus* has a Console Builder (CB) application. This facilitates the addition of new vehicles with new sensor suites to *Neptus*. *Neptus* implements a subset of the NATO standard STANAG 4586 [39] for communications with unmanned air vehicles.

Seaware is a middleware framework that addresses the problem of communications in heterogeneous environments with diverse requirements [34]. *Seaware* adopts publish/subscribe based messaging, defined by anonymous message exchange between data subscribers and publishers to provide an interface for applications to exchange data in a network through a set of transports, including Wi-Fi, RF and acoustic modems. Each application dynamically registers itself by specifying the topics it wishes to publish and subscribe without the need to know in advance who its peers are or where they are located. There is a *Seaware* node per vehicle and per operator console (one per vehicle). Each vehicle node is characterized by a topic domain identifying the vehicle to allow for a set of messages to be exchanged with the corresponding operator console.

Dune supports the implementation of the vehicle control architecture in a predictable and efficient manner for real-time performance. At the core of *Dune* there is a platform abstraction layer, written in C++, enhancing portability among different CPU architectures (Intel x86 or compatible, Sun SPARC, Intel XScale/StrongARM and IBM PowerPC) and operating systems (Linux, Sun Solaris 10, Apple Mac OS X, FreeBSD, NetBSD, Microsoft Windows 2000 or above and QNX 6.3). *Dune* can be extended in the native compiled programming language C++ or using an interpreted programming language such as Python or Lua.

We are currently developing a programming language called *DFO* ("Data Flow Objects") for embedded control software specification [33]. *DFO* allows the specification of objects with "data flow". The aims of *DFO* are basically two-fold: firstly, to allow the definition of "data flow objects" with sound and clear semantics; secondly to provide good performance and abstract details of native support in a particular platform, operating system or use of programming language for specification of "user code". Initially, *DFO* is being developed to support a set of core language constructs for: input-output data flow; mode switching (in the sense of a finite state machine); and object composition in sequential, concurrent or hierarchical fashion. The core properties we wish to attain from derived programs are determinism in execution and high performance and low memory footprint. The components of the generic vehicle control architecture have been developed and deployed with the help of *DFO* [33].

6. **Conclusions.** This paper discusses the roles of unmanned vehicle systems in future field studies (environmental, climatological, oceanographic, hydrological, etc.) in light of the recent technological developments and trends, with special emphasis on network vehicle systems.

The purpose of the paper is to stimulate the development and deployment of networked vehicle systems in these field studies over the next decades. The approach used to accomplish this goal was to present current developments in unmanned vehicle systems and networked vehicle systems before examining future trends and challenges for these deployments. Examples of developments from the Underwater Systems and Technologies Laboratory from Porto University illustrated the key points.

The contribution of the paper is descriptive, not prescriptive, in nature. It neither advocates specific concepts for networked vehicle systems, nor prioritizes the requirements. It attempts, however, to present part of the technical and technological background required for development of new research and development programs for environmental field studies. In addition, it sheds some light on some of the obstacles to practical deployments, thus attempting to contribute to the discussions conducive to their removal.

Appendix A. **List of symbols.** A list of symbols used throughout this document is shown in Table 1.

TABLE 1. List of Symbols

ADCP	Acoustic Doppler Current Profiler
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
COTS	Commercial Off-The-Shelf
CPT	Chemical Plume Tracing
CTD	Conductivity, Temperature and Depth
DTN	Delay-Tolerant Networking
GPS	Global Positioning System
GSM	Global System for Mobile communications
IMU	Inertial Motion Unit
IP	Internet Protocol
JAUS	Joint Architecture for Unmanned Systems
LAUV	Light Autonomous Underwater Vehicle from LSTS
LSTS	Underwater Systems and Technologies Laboratory (in Portuguese) from Porto University
LBL	Long BaseLine
RAFOS	SOund Fixing and RAnging, backwards
REMUS	Remote Environment Measuring UnitS
ROV	Remotely Operated Vehicle
SLAM	Simultaneous Localization and Mapping
UAV	Unmanned Air Vehicle
UUV	Unmanned Underwater Vehicle

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