HYBRID MANEUVER FOR GRADIENT SEARCH WITH MULTIPLE COORDINATED AUVs

4 AUTHORS:

Alfredo Martins
Institute for Systems and Computer Engine…
50 PUBLICATIONS **240** CITATIONS

SEE PROFILE

J.M. Almeida
Instituto Superior de Engenharia do Porto
46 PUBLICATIONS **153** CITATIONS

SEE PROFILE

E. Pereira Silva
Instituto Superior de Engenharia do Porto
62 PUBLICATIONS **199** CITATIONS

SEE PROFILE

Fernando L. Pereira
University of Porto
176 PUBLICATIONS **895** CITATIONS

SEE PROFILE

HYBRID MANEUVER FOR GRADIENT SEARCH WITH MULTIPLE COORDINATED AUVs

Alfredo Martins[+], José Miguel Almeida[+], Eduardo Silva[+], Fernando Lobo Pereira[++]

[+] *Laboratório de Sistemas Autónomos*
Instituto Superior de Engenharia do Porto
R. Dr. Antonio Bernardino de Almeida 431
4200 –072 Porto , Portugal

[++] *Faculdade de Engenharia da Universidade do Porto*
R. Dr. Roberto Frias
4200 - 465 Porto, Portugal

Abstract: This work presents a hybrid maneuver for gradient search with multiple AUV's. The mission consists in following a gradient field in order to locate the source of a hydrothermal vent or underwater freshwater source. The formation gradient search exploits the environment structuring by the phenomena to be studied. The ingredients for coordination are the payload data collected by each vehicle and their knowledge of the behaviour of other vehicles and detected formation distortions. *Copyright © 2004 IFAC.*

Keywords: coordination of autonomous robots, autonomous underwater vehicles, hybrid systems application, marine applications, plume sensing.

1. INTRODUCTION

The last two decades have been witnessing a significant increase of interest in the design and development of systems based on Autonomous Underwater Vehicles (AUV's) for oceanographic applications. The technological evolutions in sensor miniaturization, computation and communication capabilities, and power consumption efficiency enabled the design of more sophisticated vehicles and advanced navigation and control systems. This permitted to envision new missions with greater endurance, more diversified payload and navigation data (due to richer suite of payload sensors and to greater data storage capabilities), and with increased degree and more complex nature of autonomy (due to increased data processing capabilities), (Wernli 2001).

Examples of such missions include finding the location of an unknown source of an effluent in the ocean such as hydrothermal vent (Bachmeyer, *et al.* 1998), freshwater springs (Bacon, *et al* 2002, Manheim, *et al.* 2001, Silva 2002), pollution spills or wastewater discharges (Ramos, *et al* 2001), and mapping the corresponding scalar field by sampling relevant variables such as temperature, salinity, oxygen, etc. However, these missions pose new challenges in what concerns the overall framework for system's design. These triggered the emergence of a number of new research issues actively addressing the design of systems to support the functional integration of multiple heterogeneous autonomous vehicles (AV's). These range from the cooperative control of multiple AUV's (Bachmeyer and Leonard 2002) to more heterogeneous scenarios such as Autonomous Sampling Oceanographic Networks (Curtin, *et al.* 1993, Creed, *et al.* 2002) or multipurpose environmental monitoring networks.

The cooperation of multiple AUV's in a single mission can provide enormous advantages in terms of efficiency and efficacy (Silva 2002).

In the current work, we contribute to the problem of finding an underwater plume and its source location. This problem can express different oceanographic mission applications and is inspired in the surveying and search of sources of freshwater in the ocean (Silva 2002).

Underwater freshwater springs generate plumes of varying salinity. Although localised usually near to the shore, the possible survey areas are relatively large comparing to the plume dimension. The use of AUV's in survey missions can present significant advantages comparing to other methods (either indirect measuring or expensive conventional marine campaigns), since it can provide in loco salinity measurements. Multiple AUVs can extend the mission range of operation. We propose a search mission with a formation of AUVs and one Autonomous Surface Vehicle (ASV). Autonomous Surface Vehicles have been used for different tasks ranging from oceanographic missions (Manly 2000) to coordinated missions with AUV's such as in (Pascoal 2000) where the ASV acts also as a acoustic communications relay for an underwater autonomous vehicle. An absolute localisation system is required for the plume source geographical identification, and is provided by the surface vehicle. In addition, some means of relative navigation must exist for the vehicle control and formation coordination.

The formation uses a set of cooperative of small AUVs with minimal communication requirements. The use of small AUV in the study of underwater plumes has been done in (Ramos, *et al.* 2001, Fletcher 2001, Cruz, *et al.* 1999) by analysing offline the sampled data of a set of single vehicle missions.

Cooperation issues in autonomous underwater vehicles and in mobile robots in general (Baccou 2001, Bachmeyer and Leonard 2002, Bellingham, *et al.* 2002) are a strong research topic.

In (Gazi and Passino 2002), an approach based on bio-mimetics and on the study of natural swarms is considered. In this case, each vehicle is assumed to know the exact position of the others and to have an exact knowledge of the gradient. A general approach cast in the dynamic optimization framework presented in (Sousa, *et al.* 2002) shows how coordinated control problems can be treated in terms of concepts of invariance, solvability, monotonicity and switching among value functions.

Formation control of marine surface vessels is treated in (Skjtne, *et al.*2002) with the decomposition of the coordination control in a geometric task responsible for the keeping of the formation structure and a dynamic task that assigns a velocity profile to the fleet.

In (Bachmeyer and Leonard 2002) and (Leonard and Fiorelli 2001), an artificial potential approach based on the concept of virtual leader is adopted to coordinate robots with fully actuated dynamics. In the later, a gradient descent method is proposed.

Here, we present a control structure supporting the coordinated motion of a set of small AUV's enabling them to locate a freshwater spring in the ocean. We will focus in the specific maneuver of finding the minimum of a given scalar field. By appropriately interpreting the sensed data, and by using some relative navigation data, the vehicles are able cooperate in order to collectively follow a descent path of the relevant scalar field and, thus, achieve their joint goal.

Unlike (Bachmeyer and Leonard 2002), our focus on the overall implementation with AUV's reside on the logical interpretation of the sensed data in order to ensure that the set of vehicles approach the goal. Furthermore, instead of relying in a somewhat artificial potential field framework, we ensure a, in principle, stronger robustness by adopting a data driven feedback solution for the relative navigation. (Martins, *et al.*2003).

The navigation system integrated in the formation only requires relative localization and provides the minimum communication needed by the vehicles. These only use the acoustic navigation pings (without any fixed external beacons) for coordination and navigation (Martins, *et al.*2003).

In addition we consider the non-holonomy of the AUV dynamics, and integrate the kinematic constraints in the maneuver design.

The minimal communication requirement is another feature that distinguishes this maneuver from previously proposed ones. This is a particularly pertinent feature in small AUV's based systems for which energy is necessarily at a premium.

A hybrid systems approach is adopted in the design of the control scheme, being different control laws defined for the diverse phases of the maneuver. Here, we follow a methodology for the control of autonomous vehicles developed over the years at LSTS - Underwater Systems and Technologies Laboratory of FEUP – Faculdade de Engenharia da Universidade do Porto where, the Isurus AUV (Cruz, *et al.* 1999) and the IES ROV (Martins, *et al.* 1999) were.

The Autonomous Systems Laboratory at ISEP – Instituto Superior de Engenharia do Porto, has been pursuing these developments by researching advances in coordinated control as well as applications in oceanographic applications (Martins, *et al.* 2003) and football robotics (Almeida, *et al.*2003).

The motion adaptivity to the distances between vehicles of the formation and to the instantaneous navigation requirements allows the definition of strategies which are power efficient.

In the remaining of the paper, we will begin by briefly describing the problem in question. In the next section, we formulate the problem. This encompasses a physical description, the underlying requirements to be satisfied by the adopted solution, the main targeted hardware devices (vehicles, sensors, and navigation devices), and some assumptions under which the proposed control structure is designed to work.

In section 3, we describe the hybrid automaton embodying the coordinated control structure. Before presenting the main conclusions, we illustrate how the proposed control structure works.

2. PROBLEM FORMULATION

The problem in question is to develop a hybrid systems based control structure designed to support the coordinated operation of multiple AUV's for a general class of missions to detect an underwater plume in the ocean water column and to locate its spring. More specifically, we will concentrate our efforts in the design of the critical maneuver of locating the source of the plume.

2.1 Underwater plume

The plume is characterized by a scalar field in $\Re^3$, representing the measure of some physical quantity which, in the case of underwater freshwater springs, is the salinity.

Generally, in each time instant, the plume is characterized by dispersion relations (Jirka and Donecker 1991) and is strongly influenced by turbulence. Thus, the field has multiple minima and the source cannot be found by gradient methods alone (Farrell, *et al.* 2003). However, the mean time plume description provides a smooth, continuous field with a global minimum.

We consider a mean time plume model. More specifically, in the case of freshwater springs this model is characterised by:

- continuous diffusion of the salinity in the ocean,
- upward velocity of the freshwater,
- discontinuity in the plume boundary caused by phenomena detectability considerations,
- conservation of mass,
- increasing plume area with decreasing depth, and large spatial dispersion with small vertical width near the surface in the far-field relations (Jirka and Donecker 1991)

In addition, it is considered the existence of non-zero water current. This current orients the plume in a particular direction.

If we let

$$z_1 = -\log\left(K\frac{Z_{source} - z}{z}\right) \qquad (1)$$

$$r(x,y,z) = \sqrt{\left(x - vc_x \cdot z_1\right)^2 + \left(y - vc_y \cdot z_1\right)^2} \qquad (2)$$

where vc_x, vc_y, the horizontal components of the water current velocity, Z_{source} the plume source depth, the variable $m(x,y,z)$ to be sampled describing the behaviour of the plume with a logarithmic vertical profile and exponential radial horizontal mixing should satisfy the following relation:

$$m(x,y,z) = \frac{1}{\pi \cdot \sqrt{2\pi} \cdot z_1} \cdot e^{\frac{r^2}{2\log z_1}} \qquad (3)$$

A typical mean time shape for the near-field is depicted in the following figure.

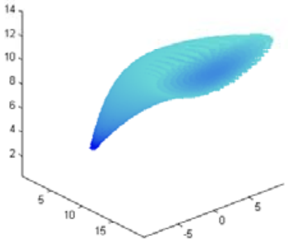

Fig. 1 The plume mean time shape.

2.2 *System requirements*

The vehicle endurance is directly related with its speed, sea state, and area to be covered. In terms of operation, the vehicle missions should have an endurance of about 100km per day (Silva 2002). This can be achieved with the currently available small AUVs, being their endurance extendable by considering a battery recharging capability at the ASV.

The navigation system should provide absolute and relative positioning information for each vehicle of the formation. This information should allow not only the control of each vehicle in order to keep the formation but also the observation of the distortions in the formation. This plays a critical role in the active search strategy. It is assumed the availability of all inter-vehicle distances and structural angles (Martins, *et al.*2003).

The consideration of mean time plume requires the sampling of instantaneous values of the physical variable of interest – salinity - and the computation of the mean time value.

As shown in (Martins, *et al.* 2003), the formation should comprise three AUVs and one ASV. This number is required by the navigation system and to ensure the features of the spatial data gathering. Additional AUVs will provide system redundancy.

Each one of the AUVs is assumed to be small, torpedo shaped with a rotating propeller, and at least two surfaces (rudder and dive plane), like *Isurus* (Cruz, *et al.* 1999). The vehicles are non-holonomic and the following kinematic model is considered for maneuver design in the horizontal plane

$$\dot{x} = v\cos\theta \qquad (4)$$

$$\dot{y} = v\sin\theta \qquad (5)$$

$$\dot{\theta} = \omega \qquad (6)$$

Bounds on the linear velocities and saturation in the control surfaces are considered in the design to allow vehicle lift control and maximum thrust bounds. These implies upper bounds the on maximum angular velocity and curvature of the vehicle motion which are taken into account in the trajectory planning for the initial survey phase of the maneuver.

The problem consists in finding the controls for each robot in order for the formation to reach a sufficiently small neighbourhood of the scalar field minimum.

3. CONTROL ARCHITECTURE

A hierarchic architecture is considered to integrate the vehicle's navigation and control systems and a hybrid systems framework was adopted in order to design control and navigation algorithms.

The global control design relies on the concept of maneuver which is modelled by a hybrid automaton (Henzinguer 1996, Lygeros, *et al.* 1999). This can be briefly described as a set of discrete states and transitions between them, being a set of controlled continuous flows associated with each one. The maneuver implementation involves not only the vehicle hybrid control law, but also the navigation filters. The control and navigation systems are integrated in the maneuver design. In addition, more complex maneuvers can be obtained by the hierarchic composition of simpler maneuvers.

The next figure depicts the information flow diagram.

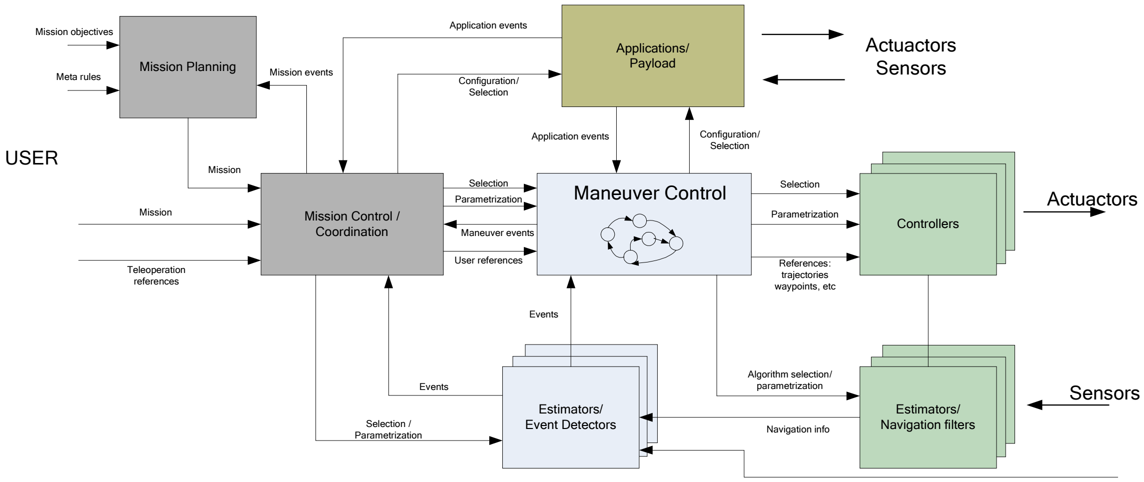

Fig. 2. Information flow diagram of the system architecture.

Each maneuver recruits and parameterises continuous lower level controllers and navigation filters. A set of event detectors supply the maneuver with transition events. The overall mission is comprised of a graph of maneuvers which can be either supplied by the user or defined by an automatic planning system.

4. COORDINATED MANEUVER

4.1 Maneuver organization

Our approach to design systems for oceanographic missions involving the coordination of multiple vehicles starts with a specification that leads to a configuration of resources able to provide the necessary requirements in terms of navigation and control. This configuration (as depicted in figure 3) consists in an Autonomous Surface Vehicle (ASV), and three AUV's. Initially, these form a tetrahedron with the AUV's at the given depth of interest forming a triangle and the surface vessel positioned above its mid point.

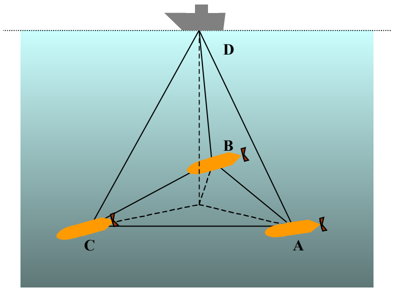

Fig. 3. The formation configuration.

During the mission execution, at least two submarines are maintained at equal depth. This constraint will be used in the navigation system to solve the angular ambiguity and does not limit the formation operational features.

As will be seen in the next section, this spatial arrangement has interesting properties for environment data sampling and features perception, and navigation.

In order to be able to coordinate the motions of the various robots, information must be shared. In this scheme, the communication activity is minimized by taking advantage of the environment structure defined by the gradient vector field in conjunction with the perception capabilities of the proposed formation geometry. This allows the motion coordination with minimal communication requirements.

The decentralized coordination is able to achieve the common goal by requiring only the partial knowledge of the other vehicles motion. In the specification of the navigation system, each vehicle is required to be able to determine all the inter-vehicle distances and some parameters of the formation attitude.

The inter-vehicle information exchange implicit in the navigation data (Martins, *et al*. 2003), thus dispensing with an underwater communication system, is one of the main innovative aspects of the proposed coordination scheme.

The considered spatial arrangement permits the covering of an area substantially larger than that of other survey methodologies. By using the localized gradient field obtained with the scalar measurements in each vehicle, the formation can detect the plume. In the phenomenon detection phase, the knowledge of the inter-vehicle distances by each vehicle can be used to detect distortions in the formation geometry. These distortions are caused by the detected variations in the scalar field and provide information to other vehicles on how it evolves in space.

The motion coordination among vehicles is, thus, achieved with a partial knowledge of the behaviours of other vehicles and, simultaneously, the sensing of the formation geometry. Upon phenomenon detection, the formation recruits another control law in order to follow the gradient leading to the minimum of the scalar field.

The vehicle control law depends on the formation state and the maneuver phase.

The characterization of the formation control structure (and, consequently, the control law for each robot) involves different discrete states corresponding to different phases of the maneuver. For each discrete state, the vehicles have different continuous control laws. Thus, a hybrid automaton (Henzinguer 1996, Lygeros, *et al*. 1999) can define the team maneuver. This hybrid nature of maneuvers is consistent with our control framework implemented in various research robots (Almeida *et al*. 2003, Martins *et al*. 2003, Silva 2002).

The coordinated maneuver phases are:

1. Survey.
2. Phenomenon detection.
3. Horizontal motion following.
4. Diving to the source.
5. Marking the source.

Additionally, several other discrete states are defined for the maneuver. These are: fault conditions or malfunctions (either in one or more vehicles, or in the formation control), intermediate formation stabilization (necessary to redefine the formation), and return to the survey phase. This last state takes place either after the marking of a source (detected by the ASV) or after false plume detection.

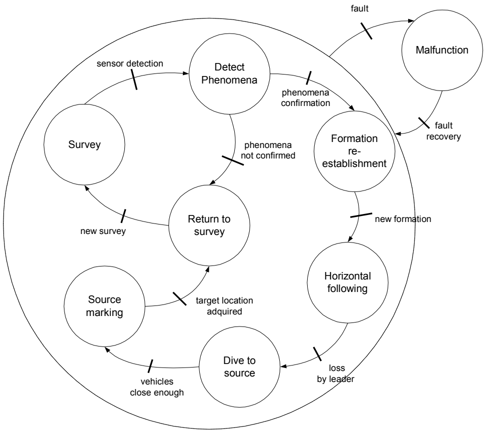

Fig. 4. Coordination maneuver state diagram

The state of the formation in three phases of the mission is depicted in the next figure.

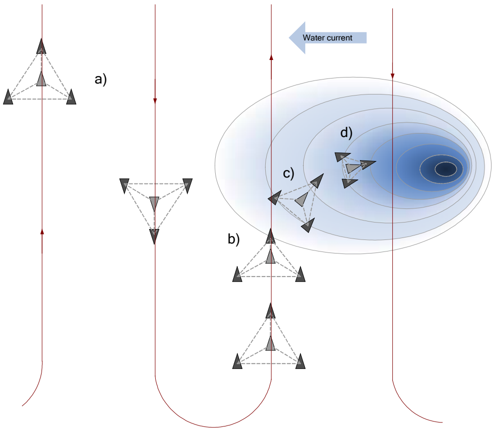

Fig. 5. Phenomenon detection.

In the initial *Survey* state, the ASV executes a "sweeping" pattern organized transversally to the estimated water current (Fig. 5a) and is followed by the three AUV's at a certain given depth, being the vertical projection of the ASV maintained at the mid point of the triangle formed by them.
Upon phenomenon detection by one of the AUVs, this one reduces the velocity and changes direction transversally to its previous motion (leading vehicle in Fig. 5b). Being the plume detection confirmed, the formation distortion introduced by the detecting vehicle is perceived by the other vehicles. Moreover, this variation in the formation can further be seen in the increase of acoustic pings since the event driven design of the navigation system adapts itself to the global formation behaviour by increasing the update rates.
In this way, the formation rotates in order to move along the direction to the plume when stabilizing the formation in *Re-establishment* state.
Then, the rear vehicles at equal depth reduce their velocity in proportion to the sensed variation of their sampled data and perform the horizontal guidance (Fig.5c). In this way, the inter-vehicle distances are a function of the norm of the sampled variable gradients, i.e., the tightness of the formation is inversely proportional to the variability of the scalar vector field (Fig. 5c, d).
Now, as motion progresses, the leading will start diving as soon as the value of the sampled vector field decreases (this meaning that otherwise it would leave the centre of the plume). In the *Dive to source* state, the maximum AUV's diving rate coupled with the horizontal guidance of the rear vehicles (kept at equal depth) forces the whole formation to rotate and dive.
When the inter-vehicle distances reach a certain threshold, the vehicles start moving in circles and the AVS marks the target location (*Source marking*). The two additional states are: *Malfunction*, usually requiring human intervention, and *Return to survey* where the vehicles move to an initial survey configuration.

4.2 Vehicle control

The AUV vertical and horizontal motions are designed separately by considering decoupled AUV models (Healey and Lienard 1993). Thus, in each maneuver phase, the controls are assumed to be: a) vehicle linear velocity v that translates into surge control and, ultimately, into propeller revolutions n, and b) vehicle angular velocity ω. This velocity is considered both in its horizontal component (yaw rate r) and vertical component (pitch rate q).
In all but the diving state, depth is constant for the three AUV's.
The vehicle control involves two terms: one reflecting the vehicle configuration in order to keep the formation, and another depending on the sampled variable value $m(\mathbf{x})$. In addition, the formation inter-vehicle distances are also a function of the sampled scalar field.
The next picture depicts the decision making variables in horizontal motion guidance.

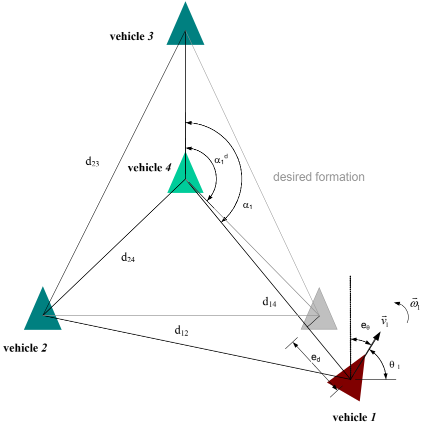

Fig. 6. Horizontal control. The point "vehicle 4" is the ASV projection in the plane formed by the AUVs.

For submarine i, controls (v, ω) are given by

$$|\vec{v}_i| = v_0 + f_1\left(d_{ij}, \alpha_i{}^d, \alpha_i, \theta\right) + f_2\left(d_{ik}\left(m(\mathbf{x}_i)\right)\right) \quad (7)$$

$$|\vec{\omega}_i| = f_3\left(d_{ij}, \alpha_i{}^d, \alpha_i, \theta\right) + f_4\left(d_{ik}\left(m(\mathbf{x}_i)\right)\right) \quad (8)$$

being v_0 the nominal speed, $\mathbf{x}_i$ the position of vehicle i, d_{ij} the inter-vehicle distances, $d_{ik}{}^d$ the desired inter-vehicle distances, $\alpha_i{}^d, \alpha_i$ the formation structural angles (desired and actual), θ vehicle orientation, $m(\mathbf{x}_i)$ the sampled variable value, j other vehicles indices, and k the maneuver state and specific vehicle role in the maneuver. Functions f_1, f_2, f_3 and f_4 depend also on the maneuver state.
The surface vehicle either acts as team leader following a predefined path (e.g., in the survey state) or follows the formation (e.g., in the diving state).
A formation of non-holonomic vehicles can be guided by distance and structural angles and by using range-bearing or range controllers (Desai *et al.* 1998) (derived by input-output linearizations). The sensing dependent terms allow to reduce the inter-vehicle distance near the plume source, and to guide the formation along the gradient.

5. CONCLUSIONS

We proposed a technically feasible integrated motion control and guidance system for a formation of AUVs and an ASV. The proposed solution involving heterogeneous vehicles was determined by its environment perception and navigation requirements.

The use of the ASV allows the absolute positioning as well as real time external tracking.

Furthermore, formation control with minimal communication requirements was also envisaged.

Each vehicle knows not only its distance to the others but also the distance between any pair of vehicles. The formation detects and follows an underwater plume with by using the sampling of the scalar field with each vehicle and the formation geometric data.

Although special attention was paid to the gradient descent problem and to practical applications of finding underwater plumes and sources, the formation topology, navigation system, control and coordination framework can be used in a wide class of oceanographic missions ranging from standard surveys (bathymetry, CTD scans, etc) to oceanic front following.

REFERENCES

Almeida, J. and A. Martins and E. Silva (2002), Control and Localisation for the ISePorto Robotic Soccer Team, *Proc. ICAR 02 – International Conf. On Advanced Robotics*, Coimbra, Portugal.

Baccou, P. et al (2001). Cooperative positioning and navigation for multiple AUV operations *Proc MTS/IEEE Oceans01*, **3**, pp. 1816-1821, Honolulu, Hawaii, USA.

Bachmeyer R. and N. Leonard. (2002). Vehicle networks for gradient descent in a sampled environment. *Proc.41 IEEE Conf. On Decision and Control*, Las Vegas , Nevada, USA.

Bachmeyer R., S. Humphris, D. Fornari, C. Van Dover and J. Howland (1998). Robotic oceanographic exploration of hydrotermal vent sites on the mid-atlantic ridge at 37º North, 32º West, *MTS Journal*, **32-3**, pp. 37-47.

Bellingham, J. and M. Tillerson, M. Alighanbari , J. How (2002). Cooperative path planning for multiple uavs in dynamic and uncertain environments. *Proc.41 IEEE Conf. On Decision and Control*, pp. 2816-2822, Las Vegas, USA.

Creed, E. and C. Mudgal, S. Glenn, O .Schofield, C. Jones and D. Webb (2002). Using a fleet of Slocum battery gliders in a regional scale coastal ocean observatory. *Proc MTS/IEEE Oceans02*, **3**, pp. 1234-1238.

Cruz, N., and A. Matos, A. Martins, J. Silva, D. Santos, D. Boutov, D. Ferreira, F. Lobo Pereira. (1999). Estuarine Environment Studies with Isurus, a REMUS class AUV. *Proc. MTS/IEEE Oceans'99 Conference*, Seattle, WA, USA

Curtin, T. and J. Bellingham, J. Catipovic and D. Webb (1993). Autonomous ocean sampling networks. *Oceanography* , **6-3**, pp. 86-94.

Desai. J. and J. Ostrowski, V. Kumar. Controlling formations of multiple mobile robots. *Proc. IEEE ICRA*, Leuven, Belgium.

Farrell, J. and W. Li, S. Pang, R. Arrieta (2003). Chemical plume tracing experimental results with a REMUS AUV. *Proc. MTS/IEEE Oceans 2003,* pp.962-968, San Diego, USA.

Fletcher, B. (2001). Chemical plume mapping with the REMUS autonomous underwater vehicle. *Proc. AUSI 12th Int. Symposium on Unmanned Untethered Submersible Technology*, Durham, USA

Gazi V. and K. Passino (2002). Stability analysis of social foraging swarms: combiend effects of attractant/repellent profiles. *Proc.41 IEEE Conf. On Decision and Control*, pp. 2848-2853, Las Vegas, USA.

Healey, A. and D. Lienard (1993). Multivariable sliding mode control for autonomous diving and steering of unmmanned underwater vehicles, *IEEE Journal of Ocean Engineering*, **OE-18**, pp327-339.

Henzinguer, T. (1996). The theory of hybrid automata, *Technical Report UBC/ERL M96/28*, Univ. California, Berkeley.

Jirka, G. and R. Donecker (1991). Hydrodynamic classification of submerged single port discharges. Journal of Water Resources Planning and Management, ASCE **117-6**.

Leonard N. and E. Fiorelli (2001). Virtual leaders, artificial potentials and coordinated control of groups. *Proc.40 IEEE Conf. On Decision and Control*, pp. 2968-2973.

Lygeros, J. and C. Tomlin, S. Sastry (1999). Controllers for reachibility specifications for hybrid systems, *Automatica*, **35**, pp. 349-370.

Manheim, F. and D. Krantz, D. Snyder, J. Madsen and B. Sturgis (2001). Streaming resistivity surveys and core drilling define groundwater discharge into coastal bays of the Delmarve Peninsula, *GSA Annual Meeting*, Nov. 5-8, Boston.

Manley, J., and A. Marsh and W. Cornforth and C. Wiseman (2000). Evolution of the autonomous surface craft AutoCat. *Proc MTS/IEEE Oceans00*, **1**, pp. 403-408, Providence, RH, USA.

Martins, A. and J. Almeida, E. Silva (2003). Coordinated Maneuver for Gradient Search Using Multiple AUVs, *Proc. MTS/IEEE Oceans2003*, San Diego, USA.

Martins,A. and N. Cruz, A. Matos, F. Lobo Pereira (1999). IES – An open system for underwater infrastructure inspection. *Proc. MTS/IEEE Oceans'99 Conference*, Seattle, WA, USA

Pascoal, A. et al (2000). Robotic ocean vehicles for marine science applications: the european ASIMOV project. *Proc MTS/IEEE Oceans00*, **1**, pp. 409-415, Providence, RH, USA.

Ramos, P. and N. Cruz, A. Matos, M. Neves , F. Lobo Pereira (2001). Monitoring an ocean outfall using an AUV. *Proc. MTS/IEEE Oceans'01 Conference*

Silva, E. (2002) .Autonomous vehicle control. *Ph.D. Thesis*, Faculty of Engineering, Porto University, Portugal, 2002 (in Portuguese).

Skjtne, R. and S. Moi, T. Fossen (2002), Nonlinear formation control of marine craft. *Proc.41 IEEE Conf. On Decision and Control*, pp. 1699-1704, Las Vegas, Nevada, USA.

Sousa, J. and A. Matos , F. Pereira (2002). Dynamic optimization in the coordination and control of autonomous underwater vehicles. *Proc.41 IEEE Conf. On Decision and Control*, pp. 2087-2092, Las Vegas, Nevada, USA.

Wernli, R (2001). AUV Commercialization – Who's leading the pack? *Proc. MTS/IEEE Oceans'01 Conference.*