Coordinated Maneuver for Gradient Search Using Multiple AUVs

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***Abstract*- The coordinated use of multiple Autonomous Underwater Vehicles can provide important advantages for oceanographic missions. One important mission application scenario can be the search of underwater plumes such as sources of freshwater of hydrotermal vents. These plumes characterize the environment by creating a gradient field of some measurable physical quantity.**

An innovative integrated acoustic navigation system and coordination control maneuver for a formation of 3 AUVs and 1 surface craft to gradient search and following missions is proposed. The specific formation geometry and topology takes in account the navigation and coordination requirements. It was designed to achieve an efficient , low cost and technically feasible solution.

The system can operate in 3 modes depending on formation distances. Varying pinging rates and offsets are used to communicate parameters and mode changing. No additional underwater communication systems neither acoustic transponder deployment are needed for the vehicle coordination. This way a high degree of energy efficiency and overall mission low cost and simpler logistics is achieved.

The hybrid nature of the coordinating maneuver allows the formation gradient survey and following with the efficient exploitation of the environment structuring by the phenomena to be studied. The individual control laws were designed in order to minimize the inter-vehicle communication. The coordination factors are the knowledge by the vehicles of each other behavior (since all vehicles execute the same control laws) and the detection of formation distortions. These distortions are detected by the relative navigation system.

The proposed approach allows the low cost implementation of a multiple AUV coordinating control for a large range of oceanographic missions.

I. INTRODUCTION

The uses of Autonomous Underwater Vehicles (AUV) for oceanographic tasks have been presented in the literature in the last two decades. Existing vehicles have been presenting continuous advances in incorporation of technology, advanced navigation and control functionalities, longer missions, flexibility and capacity of payload and a very diverse suite of sensors [1].

A vast number of problems related with AUVs are still under active research and recently much effort has been directed towards the use and integration of multiple vehicles in heterogeneous cooperative frameworks. These can span from the cooperative use of multiple vehicles in missions [2] to more heterogeneous scenarios such as Autonomous Sampling Oceanographic Networks [3, 4] or multipurpose environmental monitoring networks.

The cooperation of multiple AUVs in a single mission can provide enormous advantages in terms of efficiency and efficacy [17,18].

Cooperation issues in autonomous underwater vehicles and in mobile robots in general [2,5] are a strong research topic.

In [6], an approach based on biomimetics and on the study of natural swarms is taken. 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 theoretical approach with dynamic programming is used in [7] to show that the control and coordination problems can be treated in terms of concepts of invariance, solvability, monoticity and switching among value functions.

Formation control of marine surface vessels is treated in [8] 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 [9] an artificial potential approach is taken to the coordination of robots with fully actuated dynamics. This approach assumes the existence of virtual leaders and in [2] a gradient descent method is proposed.

Our approach proposes a gradient descent solution but unlike [2] is focused on the overall implementation with AUV's. Thus we propose a relative acoustic navigation system specified taking in account the coordination requirements. In addition we consider the non-holonomy of the AUV dynamics, and integrate the kinematic restrictions in the maneuver design.

In this work, a coordinated control strategy is presented for the use of multiple AUVs for gradient search tasks.

These tasks can arise from the need to map an underwater hydrothermal vent or finding the location of an unknown source of water (with different characteristics such as: freshwater or pollution) in the ocean. The use of small AUV in the study of underwater plumes has been done in [10, 11] by analyzing offline the sampled data of a set of single vehicle missions.

The presented control maneuver also differs from previously works, in low communication requirements for the vehicles and in its hybrid control approach.

A hybrid systems approach is taken in the definition of the control scheme, and different control laws are presented for several phases of the maneuver. This is an extension of the methodology previously used in the control of AUVs and mobile robots. At the Underwater Systems Lab - Faculty of Engineering of Porto (LSTS-FEUP) and Autonomous Systems Lab - Institute of Engineering of Porto (LSA-ISEP), the Isurus AUV [12] and the IES ROV [13] are example of the methodology.

The navigation system proposed 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.

Our proposed coordination maneuver and navigation system has a very high power efficiency since is adaptive to the distances of the formation and the instantaneous navigation requirements.

In the remaining of the paper we will begin by briefly describing the problem in question. In the following section the navigation system is addressed and a particular attention is taken to the requirements imposed to and to be imposed to the control maneuver. The maneuver is treated in section IV and finally some concluding remarks are made in section V.

II. PROBLEM FORMULATION

The problem in question is to develop a suitable navigation and control framework for a set of underwater vehicles to perform coordinated oceanographic missions. These can consist in the following and descend of an oceanic gradient field. Diverse marine phenomena such as hydro-thermal vents [14], underwater springs [15, 16, 17, 18], wastewater discharges [10] or pollution spills can originate this field. The scalar field can be a temperature, salinity, or other water measurable characteristic.

In the current work, we will consider more specifically 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 [17, 18].

Consider the environment structuring scalar field, defining the water property to be measured:

$$M(\mathbf{x}) : \mathbb{R}^3 \to \mathbb{R}$$

$$M(\mathbf{x}) = \begin{cases} m_1 : x \notin S_{plume} \subset \mathbb{R}^3 \\ m(\mathbf{x}) : \mathbf{x} \in S_{plume} \subset \mathbb{R}^3 \end{cases}$$

$$\exists^1 \mathbf{x} \in S_{plume} : \nabla m(\mathbf{x}) = \mathbf{0}$$

(without loss of generality we can normalize the scalar field between 0 and 1). Consider also S_{AUV} a set of underwater vehicles. Each vehicle has in general 6 degrees of freedom. The vehicle dynamics are given by non-linear differential equation (possibly not known). The problem is to find the controls for each robot in order for the formation to reach a sufficiently small neighborhood of the scalar field minimum (the source)

Our approach to solve the problem of coordinated multiple-vehicle oceanographic missions consists in a specific configuration providing the necessary requirements in terms of navigation and control. This configuration (as depicted in the following figure) consists in an Autonomous Surface Vehicle (ASV), and three AUV's. These form initially a tetrahedron with the AUV's at the same depth and the surface vessel positioned above the middle of the triangle formed by the submarines.

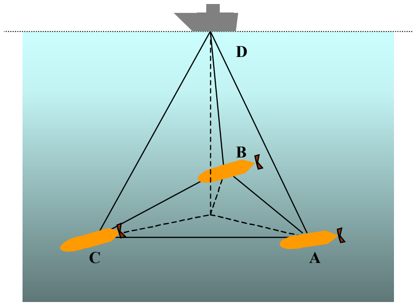

Fig. 1. Formation configuration

Eventually and depending on the mission objectives (survey, gradient descent, etc) the AUV's can move at different depths, with the restriction of maintaining at least 2 of them at the same depth. This restriction will be used in the navigation system to solve an angular ambiguity and does not limit the formation operational characteristics.

This spatial arrangement (as will be seen in the following sections) has interesting properties in terms of environment measurement and perception, and overall navigation.

III. NAVIGATION

Oceanographic missions or more specifically gradient following/searching missions require the positioning of the vehicle or team of vehicles. The localization is used for two purposes: vehicle navigation in order to accomplish the mission objectives, and for geographic and spatial correlation of gathered data.

An acoustic navigation system that assures both objectives is proposed.

The system has to meet a set of requirements:

- Endorse each vehicle with the information needed to keep the formation (distance between all the formation vehicle and angles)
- Low energy consumption (adaptive ping strategy, allows different measurement rates depending of actual perception requirement of each vehicle in our solution)
- Low cost (only LBL, compass and GPS)
- No need for environment infra-structuring (such as fixed transponder deployment)
- Be able to sense discrete events need by the control
- Allows an additional off-line global positioning of all the environment samples.

For the low energy consumption requirement to be met several conditions are necessary:

- Short distances between vehicles requiring less ping power
- adaptive ping strategy, allowing different ping rates depending of actual perception requirement of each vehicle

Additionally, the short formation distances allow the use of high signal frequency tones. That will contribute to the signal attenuation and reducing the acoustic noise and multi-echo problems. On other hand, a reduction of the ping duration can be achieved, contributing to increasing measurement precision

The acoustic signals can be a multi-frequency single tones (such as the ones in [19, 20]) or digitally signed acoustic pulses.

With this system is possible to achieve relative localization for the set of underwater vehicles. However, for the purpose of oceanographic missions an absolute positioning of the gathered data is necessary. The solution to deploy acoustic transponders at fixed known positions [3, 19, 20, 21] has high operational costs. Other solution is to provide a known absolute reference point for the overall network of vehicles. The use of an autonomous surface craft in conjunction with an AUV has been done for localization of the underwater vehicle and high-speed acoustic communication (taking advantage of the vertical acoustic channel). We propose the use of the surface vehicle equipped with GPS and the necessary acoustic transponders to position the underwater fleet of vehicles. The latter solution provides significative advantages in terms of operation costs and operational simplicity.

In addition it is assumed that the internal clocks of each vehicle (AUVS and ASV) are synchronized. It is relatively easy with conventional methods and protocols such as NTP to synchronize system clocks to a precision sufficient for navigation purposes [22, 23].

Each vehicle emits at a predefined instant of time a identification pulse. The others respond with a different signal upon the reception of an identification pulse. Since every vehicle listens all the signals, it is possible for each vehicle to determine the distances between each other two vehicles. The process is repeated cyclically at a constant rate (determined in order to allow the worst case of communication delay).

The acoustic navigation system is highly tied with the formation coordination and control. In addition the mission objectives and phenomena characterization have profound impact on both the navigation and control requirements.

For instance, the convenient inter-vehicle distances can depend on the size of the phenomena to be observed (plume or gradient) and also can change during mission execution.

According to distance the communication system can operate in 3 modes: compact, semi-compact and full.

These modes correspond to the time scheduling of pings and responses. They maximize the navigation update rate and use of acoustic channel without degrading signal-to-noise ratios.

In the following figure, one can observe the semi-compact navigation scheme used in medium range distances. An estimated time-of-flight (TOF) of 60ms is assumed (90m between vehicles) and also an equilateral pyramid geometry. Each vehicle pings in turn and only after all the responses are issued and received the cycle can be repeated. There are offsets in each vehicle pinging rate and delays in responses to reduce acoustic medium cluttering.

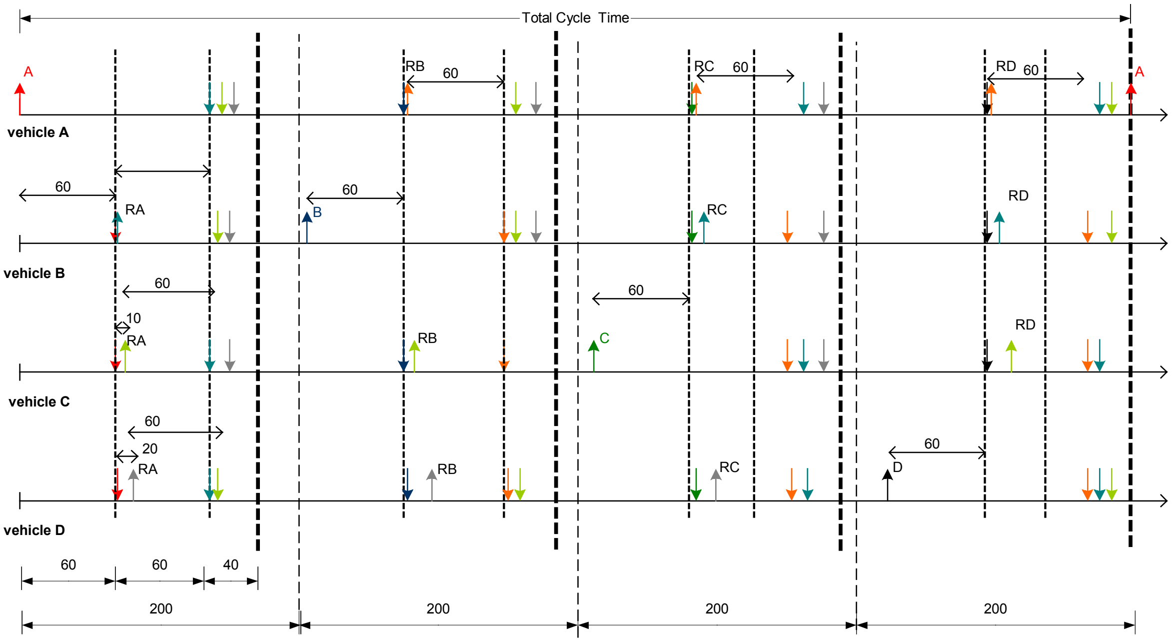

Fig. 2. Acoustic navigation scheme (semi-compact mode)

The compact mode is presented on the next figure where a relative large distance is assumed (in this case 300m corresponding to 200ms of TOF). Here all the vehicles emit their id signal in sequence on an initial phase, followed by a response step and a response-receiving phase.

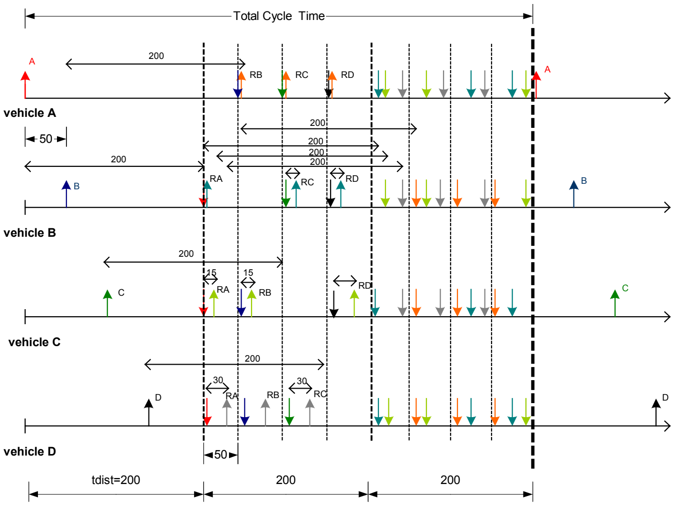

Fig. 3. Compact acoustic navigation mode

The delays shown in the responses to ping signals have the following causes:

- Intentional delay introduced by the answer vehicle, depend on the pair {Vehicle Ping, vehicle answer} – to avoid acoustic overlap
- Measurement error due to the motion of the receptor.
- Intentional delay to send information.
- Delay to avoid answer overlap at short distances

IV. COORDINATED MANOUVER

A coordinated control of multiple agents (in this case multiple robots) can include shared objectives, shared resources and shared information. The coordination implies the dependence of each robot control/decision process by the state of the other robots or by pursuing of a global common objective. The existence of shared resources imposes restrictions on the global process. In the present case, there is no physical shared resource. However, the access to the acoustic medium (in order to minimize multi-path and maintain good signal-to-noise ratios) must be managed carefully. The acoustic medium can be considered thus a common resource between the set of robots. This management, as seen in previous sections, is achieved with a careful use of the time of ping and expected times of flight (dependent on the distances) with conjunction with a set of safeguard offsets.

The formation global objective consists in detecting and following the gradient field. As mentioned before, this objective can be translated to detecting the source of an oceanic plume (freshwater source, hydrotermal vent, etc).

To be able to coordinate the motions of the various robots, information must be shared. In the current case, this communication is kept at a minimum, by taking advantage of the structuring of the environment by the gradient field in conjunction with the perception capabilities of the proposed formation geometry allowing the specification of a coordinated control with minimum requirements.

It is possible for the decentralized coordination to achieve the common goal requiring only the partial knowledge of the other vehicles dynamics. The acoustic navigation system specification presented before considered the requirement for each vehicle to be able to determine all the inter-vehicle distances (and some additional formation attitude parameters).

One of the main innovations of the proposed coordination scheme is the inter-vehicle communication embodied in the navigation system. Thus there is no need for a specific underwater communication system.

The spatial arrangement permits the covering of a relatively large area (compared with other survey methodologies). Using the localized gradient field and with only scalar measurements in each vehicle, the formation can detect the plume. In the phenomena detection, 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 specific vehicle control laws to inform the vehicles of which one has detected variations in the field.

Each vehicle coordinates its motion with the others by knowing a model of the other vehicle behavior (control law) and simultaneously sensing the formation geometry.

Upon phenomena detection, the formation assumes different control laws to follow the gradient and detect its minimum (source).

The vehicle control laws depend on the formation state and the phase of search.

The characterization of the formation control (and consequently each robot control law) implies the existence of different discrete states corresponding to different search phases. For each discrete state the vehicles have different continuous control laws. Thus, a hybrid automaton [24,25] can define the team maneuver. This hybrid control systems nature of the maneuvers is consistent with our control framework implemented in various research robots [13, 17, 26].

The coordinated maneuver phases are:

1. Survey
2. Detect phenomena
3. Horizontal following
4. Dive to the source
5. Marking the source

Additionally several other discrete states are defined for the maneuver. These are fault condition or malfunction (in one, various vehicles or in the formation control); intermediate formation establishment (necessary to redefine the formation) and return to survey. This last state corresponds to the return to the survey either after the marking of a source (detected by the ASV) or by false plume detection.

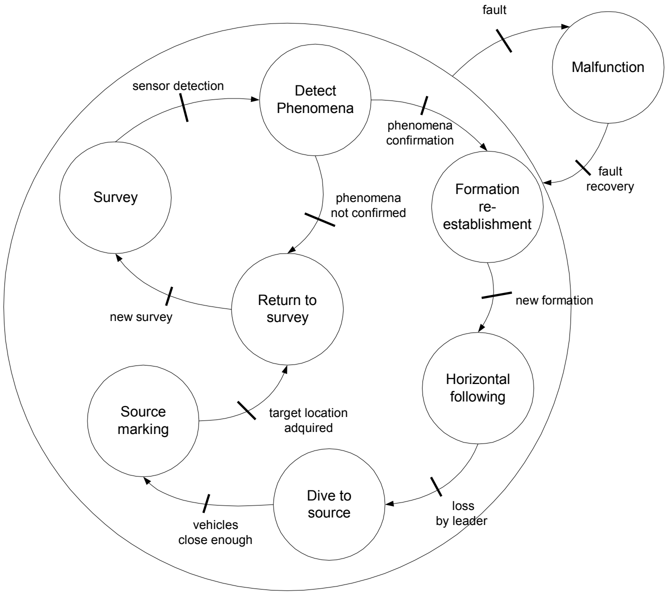

Fig. 4. Coordination maneuver state diagram

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

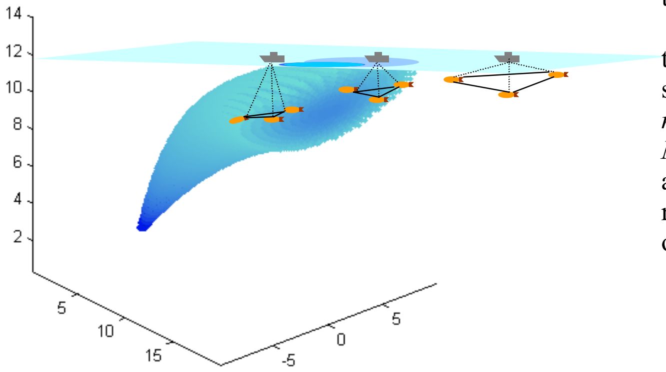

Fig. 5. Different mission phases example

In the initial *Survey* state, the ASV executes a “sweeping” pattern. The 3 AUVs follow the surface vehicle at a small fixed depth and maintain the vertical projection of the boat at the middle of the triangle formed by them.

Upon the trace detection of the phenomenon by one of the AUVs, this AUV reduces velocity and changes direction to a perpendicular to its previous movement. If the plume is confirmed the formation distortion introduced by the detecting vehicle is perceived by the others. This change of formation can also be reflected in the increase of acoustic pings since the navigation system adapts itself to the global dynamics (with the previous very steady state movements there is no need for faster update rates).

The formation hence turns to move along the direction to the plume in the *Re-establishment* state.

At a same depth the rear vehicles reduce velocity depending on the sensed measurements and perform the horizontal guidance (as seen in the next figure for the *Horizontal following*). Additionally the desired inter-vehicle distances are a function of the measurements. Thus with the decrease (increase) of the field, the formation gets tighter.

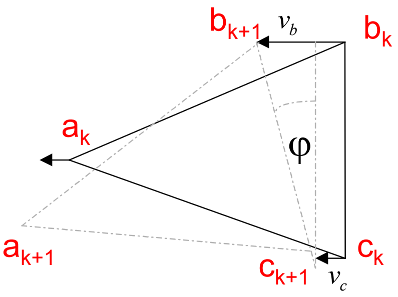

Fig. 6. Formation guidance by the rear vehicles in the *horizontal following* state.

As soon as the front vehicle starts to leave de center of the plume, situation detected by the increase in the measurements it starts to dive. In the *Dive to source* state the physical maximum dive rate of the vehicles coupled with the horizontal guidance of the rear ones (that are kept at same depth) forces the formation to rotate and dive towards the source of the phenomenon.

When the inter-vehicle distance reaches a minimum threshold the vehicles start to move in circles and the surface vessel acquires the target location (*Source marking*). There are also two additional states, a general *Malfunction* state that usually requires human intervention and a *Return to survey* state where the vehicles ascend and return to the initial survey configuration (after a successful or unsuccessful search).

V. CONCLUSIONS

We proposed a technically feasible navigation and control system for a formation of autonomous underwater vehicles and an autonomous surface craft. The proposed specific heterogeneous solution was determined by its environment perception capabilities and directly related to the developed navigation system. A high performance, low cost and low energy acoustic navigation system was designed.

Low cost absolute positioning of a network of auvs, with advantages versus standard environmental instrumentation can be achieved. The use of the ASV allows not only the absolute positioning but also the real time external tracking of the survey.

Formation control without additional communication systems is also proposed. Parameters can be communicated by changing the offset in the pinging times on the localization system. And discrete states can be perceived by the pinging activity.

Each vehicle knows not only its distance to the others but also de distance between all the others. The formation detects and follows an underwater plume (gradient) with only scalar measurements in each vehicle and knowledge of the its geometry.

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

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