NONLINEAR MOTION CONTROL OF MULTIPLE AUTONOMOUS UNDERWATER VEHICLES

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Abstract: This paper addresses the problem of steering a group of underactuated Autonomous Underwater Vehicles (AUVs) along given spatial paths, while holding a desired inter-vehicle formation pattern. Exploiting Lyapunov-based techniques and graph theory a decentralized control law is derived that takes into account both the dynamics of the cooperating vehicles, the constraints imposed by the topology of the inter-vehicle communications network, and the cost of exchanging information. The CPF problem is divided into the motion control task of making each vehicle track a virtual target moving along the desired path, and the dynamic assignment task of adjusting the speeds of the virtual targets so as to achieve vehicle coordination. At the path-following level, the controller derived exhibits an inner-outer loop structure. Convergence and stability of the overall system are proved formally. Simulations results are presented and discussed.

Keywords: Autonomous underwater vehicles, Coordinated path-following, Coordination control, Graph theory, Nonlinear control, Underactuated systems

1. INTRODUCTION

Recent technological advances have spurred a broad interest in autonomous, adaptable vehicle formations. The development of powerful control techniques for single vehicles, the explosion in computation and communication capabilities, and the advent of miniaturization technologies have raised interest in vehicles which can interact autonomously with the environment and other vehicles to perform, in the presence of uncertainty and adversity, tasks beyond the ability of individual vehicles. The concept is based on the idea that a monolithic structure can be distributed in an inexpensive network of vehicles, resulting in a significant improvement in efficiency, performance, reconfigurability and robustness, and in the emergence of new capabilities. The types of applications envisioned are numerous.

Spacecraft formation flying is involved for example in autonomous rendezvous and docking missions. Recently, considerable interest has been focused on microsatellite clusters that have the advantage, over large and complex single-purpose satellites, to expand functionality, distribute risk, and reduce cost. Further examples of spacecraft formation flying can be found in (Beard *et al.*, 2001; Mesbahi and Hadaegh, 2001).

Advances in avionics, GPS-based navigation, and flight control techniques have brought unmanned aerial vehicle (UAV) technology to a point where it is routinely used in commercial and military applications, leading to renewed interest in **UAV formation flight** (Fax, 2002). Applications of this technology include air-to-air refueling, military maneuvers and drag reduction via close formation flight (see Giuletti *et al.*, 2000, and the references therein).

Considerable work has been done in the field of **coordinated control of land robots** (Desai *et al.*, 1998; Ögren *et al.*, 2002; Ghabcheloo *et al.*, 2007). A broad international effort is being made for the development of an *Automated Highway System* (AHS) that would improve safety by avoiding collisions, and increase vehicle throughput, thus reducing traffic (McMillin and Sanford, 1998; Horowitz and Varaiya, 2000).

Following the recent advances in marine technology there has been a surge of interest worldwide in the development of autonomous surface crafts (ASCs) and underwater vehicles (AUVs) capable of exploring the oceans to collect data. In numerous other scenarios there are several disadvantages in using one single vehicle: among them lack of robustness to single point failure and inefficiency due to the fact that the vehicle might need to wander significantly to collect rich enough data. A cooperative network of vehicles has the potential to overcome these limitations and can adapt its behaviour/configuration, both *i)* in response to the measured environment, in order to improve performance and optimize the detection and measurement of fields and features of particular interest, or *ii)* in case of failure of one of the vehicles. Furthermore, in a cooperative mission scenario, each vehicle may only be required to carry a single sensor making each of the vehicles in the formation less complex then a single heavily equipped vehicle, thus increasing the reliability of the ensemble (Aguiar and Pascoal, 2007*a*). A detailed introduction to this subject can be found, along with other examples, in (Stilwell and Bishop, 2000; Encarnação and Pascoal, 2001; Fossen, 2002; Skjetne *et al.*, 2002).

2. PROBLEM STATEMENT

From a theoretical viewpoint, the problems that must be solved to achieve coordination of multiple vehicles cover a vast number of fields that include navigation, guidance, and control. This thesis focuses on coordinated path-following, where multiple vehicles are required to follow pre-specified spatial paths while keeping a desired inter-vehicle formation pattern. This subject poses different and unique challenges in each of the areas of application reviewed in the previous section. However, as pointed out in (Fax and Murray, 2004) several common threads can be found. Two in particular are worth stressing:

i) In most cases (the main exceptions being in the area of aircraft control) the vehicles are coupled through the task they are required to accomplish together, but are otherwise dynamically decoupled, that is, the motion of one vehicle does not directly affect the others.

ii) Decisions must be made by each vehicle using only limited information about the other vehicles, as communications are restricted by the nature of the supporting network and may be subject to uncertainty and transmission delay.

The highly distributed nature of the vehicles' sensing and actuation modules one one side, and the strong practical limitations to the flow of information among vehicles on the other, require the adoption of a new control paradigm that departs considerably from classical centralized control strategies, in which a single controller possesses all the information needed to achieve the desired control objectives (Ghabcheloo *et al.*, 2006*a*). For these reasons, there has been over the past few years a flurry of activity in the area of multi-agent networks with application to engineering and science problems. Namely, in such topics as parallel computing (Tsitsiklis and Athans, 1984), synchronization of oscillators (Sepulchre *et al.*, 2003; Papachristodoulou and Jadbabaie, 2005), collective behavior and flocking (Jadbabaie *et al.*, 2003), consensus (Lin *et al.*, 2007), multi-vehicle formation control (Egerstedt and Hu, 2001), asynchronous protocols (Fang *et al.*, 2005), and graph theory and graph connectivity (Kim and Mesbahi, 2006).

In spite of significant progress in all these areas, much work remains to be done to develop strategies capable of yielding robust performance of a fleet of vehicles in the presence of complex vehicle dynamics, severe communication constraints, and partial vehicle failures. These difficulties are specially challenging in the field of marine robotics for two main reasons:

i) The dynamics of marine vehicles are often complex and cannot be simply ignored or drastically simplified for control design purposes.

ii) Underwater communications and positioning rely heavily on acoustic systems, which are plagued with intermittent failures, latency, and multipath effects. These effects set tight limits on the effective communication bandwidths that can be achieved and introduce latency in the measurements that are exchanged among the vehicles.

It is in this framework that this thesis *proposes a decentralized control structure where the dynamics of the cooperating vehicles and the constraints imposed by the topology and the nature of the inter-vehicle communications network are explicitly taken into account.*

3. PROBLEM SOLUTIONS

3.1 Motion control of underactuated vehicles

For fully actuated systems, the problems of trajectory-tracking and path-following are now reasonably well understood. However, for underactuated autonomous vehicles, *i.e.*, systems with a smaller number of control inputs than the number of independent generalized coordinates, they are still active research topics. The study of these systems is motivated by the fact that it is usually costly and often impractical (due to weight, reliability, complexity, and efficiency considerations) to fully actuate autonomous vehicles (Aguiar and Hespanha, 2003). Typical examples of underactuated systems include robot manipulators, wheeled robots, walking robots, spacecraft, aircraft, helicopters, missiles, surface vessels, and underwater vehicles. The motion control problem for underactuated vehicles is especially challenging because most of these systems are not fully feedback linearizable and exhibit nonholonomic constraints. A class of underactuated vehicles that poses considerable challenging in control system design is the class of marine underactuated vehicles. These vehicles exhibit complex hydrodynamic effects that must necessarily be taken into account.

Encarnação *et al.* (2000) and Encarnação and Pascoal (2000) propose Lyapunov based control laws to solve the path-following problem for a single autonomous underactuated vehicle. The advantage of nonlinear control when compared with classical contol strategies is that it explicitly exploits the physical structure of the vehicles, instead of opposing it. The path-following problem is divided into a dynamic and a kinematic task, the latter consisting in making the Serret-Frenet frame $\{\mathcal{F}\}$ associated to the vehicle track a frame attached to the closest point on the path. This strategy exhibits severe limitations, as the initial position of the vehicle has to lie inside a tube around the path, the radius of which has to be smaller than the smallest radius of curvature present in that path.

The solution proposed in (Lapierre *et al.*, 2003*b*) lifts these restrictions by controlling explicitly the rate of progression of a "virtual target" to be tracked along the path, that is, the Serret-Frenet frame is not attached to the point on the path that is closest to the vehicle. Instead, the origin of $\{\mathcal{F}\}$ is made to evolve according to a conveniently defined control law, effectively yielding an extra control variable. The same strategy is adopted and refined in (Aguiar and Hespanha, 2003, 2004, 2007; Aguiar and Pascoal, 2007*b*), where parametric modeling uncertainties are considered.

Borrowing from these results, in this thesis *we decouple the motion control problem, designing independently an inner-loop dynamic controller and an outer-loop kinematic controller that produces the speed reference for the inner loop.* The reason behind this choice is that most autonomous underwater vehicles are equipped with an inner-loop controller that regulates the thrusters so that the surge speed and yaw rate follow a given reference. Although better results could be achieved, in terms of saturation and smoothness of the control signal, designing one single controller, decoupling the problem results in *greater portability*, as the kinematic control laws obtained can be applied to a wide range of AUVs. A second contribution is to consider the case in which only some elements of the kinematic and dynamic states are available to the controllers. There are two main practical motivations:

i) The sway velocity sensors are very expensive, and it is therefore interesting to see how the performance of the control system is limited by their absence.
ii) The approach adopted in deriving the control laws for the inner and outer loop imply that the inner-loop controller has no access to the time derivative of the reference speed.

We therefore design the trajectory-tracking and path-following controllers assuming, first, that there are no restrictions in terms of accessible variables, then introducing the limitations above and proving that the stability and convergence properties still hold under some reasonable assumptions.

3.2 Coordinated control of multiple AUVs

The results of (Encarnação *et al.*, 2000; Encarnação and Pascoal, 2000) are applied, in (Encarnação and Pascoal, 2001), to the coordination control of an autonomous surface craft (ASC) and an autonomous underwater vehicle (AUV). However, the strategy adopted is not easily generalized to more than two vehicles and requires the exchange of a large amount of information between them.

A more general approach to coordinated path-following can be found in (Egerstedt and Hu, 2001), where the formation is defined as the global minimum of a "rigid body constraint function", and in (Skjetne *et al.*, 2002, 2003; Lapierre *et al.*, 2003*a*). The common thread is to divide the problem in a motion control task, to be solved individually for every vehicle, each having access to a set of local measurements, and a dynamic assignment task, consisting in synchronizing the parametrization states that capture the along path distances between the vehicles. This strategy, that is also the one adopted in this thesis, results in decoupling path-following (in space) and inter-vehicle coordination (in time). Notice however that the aforementioned works do not consider the communication constraints imposed by the topology of the inter-vehicle communications network.

The topics of information flow and cooperation control of vehicle formations are addressed in (Fax and Murray, 2002*a*,*b*), that propose a methodology based on a framework that involves the concept of Graph Laplacian, a matrix representation of the graph associated with a given communication network. In particular, the results in (Fax and Murray, 2002*a*) show clearly how the Laplacian plays a key role in assessing stability of the behavior of the vehicles in a formation.

In (Ghabcheloo *et al.*, 2006*b*, 2007) this methodology is used to obtain coordination laws that hold in case of communication losses and time-delays. Is it assumed, however, that the flow of information is continuous, even though it may exhibit intermittent interruptions. Borrowing from (Yook *et al.*, 2002; Xu and Hespanha, 2006), the work in (Aguiar and Pascoal, 2007*a*) addresses explicitly the fact that inter-vehicle communications do not occur in a continuous manner, but take place at discrete instants of time.

The third contribution of this thesis is then to propose an approach *that aims at reducing the frequency at which information is exchanged among the systems involved*, extending the results of (Aguiar and Pascoal, 2007*a*) and focusing on the simulation of formations with a higher number of vehicles. A subset of the results reported here were presented in (Vanni *et al.*, 2007*a*,*b*; Aguiar *et al.*, 2007).

4. ILLUSTRATIVE EXAMPLE

Computer simulations were done to illustrate the performance of the CPF controller proposed, when applied to a group of three AUVs. The numerical values used for the physical parameters match those of the Sirene AUV, described in (Aguiar, 1996). The AUVs are required to follow a lawn mower path, typical in ocean exploration scenarios, while keeping a triangular formation pattern. To test the robustness of the control system, noise is added to both position and velocity sensor measurements. Vehicle 1 is allowed to communicate with AUVs 2 and 3, but the latter two do not communicate between themselves directly. To further illustrate the behavior of the proposed CPF control architecture, we also force the following scenario: from $t = 300$ s to $t = 350$ s, the coordination state of AUV 3 cannot increase. Fig. 1 shows the trajectories of the AUVs. The orientation of the vehicles is always such to compensate the effect of the water current. Fig. 2 shows the convergence of the path-following error (a) and of the coordination error (b), which however increases when γ_3 is forced to stop. The variables σ_i in Fig. 2 (c) assume value 1 when vehicle 1 or

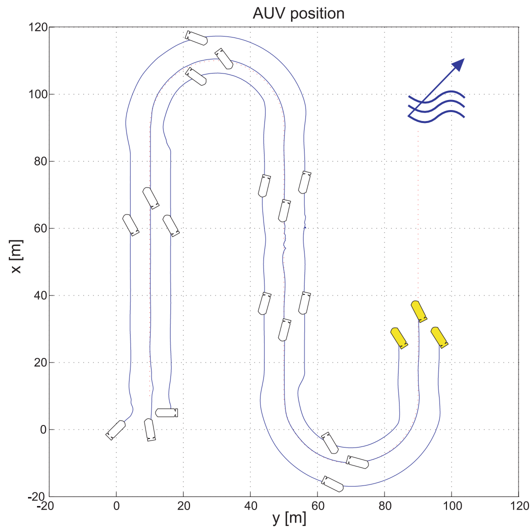

Fig. 1. Trajectory of the AUVs on the x-y plane

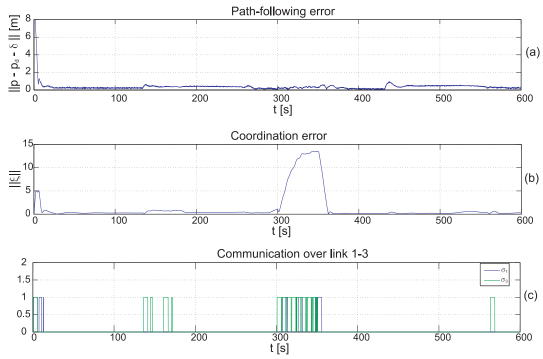

Fig. 2. Norm of the total path-following error (a), norm of the coordination error (b) and communication over link 1-3 (c)

vehicle 3 send a message over link 1-3. Note the reduced frequency of data exchanges in the overall period. The vehicles only need to communicate briefly at the beginning of the simulation, to synchronize their parametrization states, and during the curve parts of the trajectory. The communication rate increases when AUV 3 is forced to slow down.

5. CONCLUSIONS

This thesis addresses the problem of coordinated motion control for a group of underactuated autonomous underwater vehicles. The solution proposed builds on Lyapunov based techniques and is valid for a large class of underwater underactuated vehicles. Furthermore it addresses explicitly the constraints imposed by the topology of the inter-vehicle communications network, and it leads to a decentralized control law with reduced exchange of data among the vehicles is kept at a minimum. Simulations illustrate the efficacy of the solution proposed.

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