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COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems
Session 2 - Advances in Control Theory and Control Engineering
Session 3 - Optimisation and Management of Complex Systems and Networked Systems
Session 4 - Intelligent Vehicles and Mobile Systems
Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Ch. Ament

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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2 Advances in Control Theory and Control Engineering

52^{nd} Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
10 – 13 September 2007

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Coordinated Path Following of Multiple Marine Vehicles: Theoretical Issues and Practical Constraints

Abstract

We address the problem of making a group of marine vehicles follow pre-determined paths while keeping a desired spatial formation pattern (coordinated path following). We provide a brief summary of recent work in the area, leading to challenging theoretical issues that bear affinity with those that arise in Networked Control Systems. Practical constraints imposed by the underlying inter-vehicle acoustic communications network are discussed. The paper surveys some of the solutions developed so far and contains the results of simulations that illustrate the potential of the methodologies developed for coordinated path following.

Introduction

Spawned by the advent of small embedded processors and sensors, advanced communication systems, and the miniaturization of electro-mechanical devices, there is widespread interest in the design and deployment of groups of networked autonomous robotic vehicles operating in a number of challenging environments. Some of the potential applications include searching and surveying operations, as well as exploration and habitat mapping in hazardous environments.

A particular important scenario that motivates the cooperation of multiple autonomous vehicles and poses great challenges to systems engineers, both from a theoretical and practical standpoint, is *automatic ocean exploration/monitoring for scientific and commercial purposes*. In this scenario, one can immediately identify two main disadvantages of using a single, heavily equipped vehicle: lack of robustness to system failures and inefficiency due to the fact that the vehicle may need to wander significantly to collect data over a large spatial domain. A cooperative group of vehicles connected via a mobile communications network has the potential to overcome these limitations. It can also reconfigure the network in response to measurements of the environment in order to increase mission performance and optimize the strategies for detection and measurement of vector / scalar fields and features of particular interest. Furthermore, in a cooperative mission scenario each vehicle may only be required to carry a single sensor (per environmental variable of interest) making each of the vehicles in the formation less complex, thus increasing its reliability.

As an example, Figure 1 captures a conceptually simple mission scenario where an autonomous surface craft (ASC) and an autonomous underwater vehicle (AUV) maneuver in synchronism along two spatial paths, while aligning themselves along the same vertical line, so as to fully exploit the good properties of the acoustic communications channel under these conditions. This is in striking contrast to what happens when communications take place at slant range, for this reduces drastically the bandwidth of the channel, especially due to multipath effects in shallow water operations.

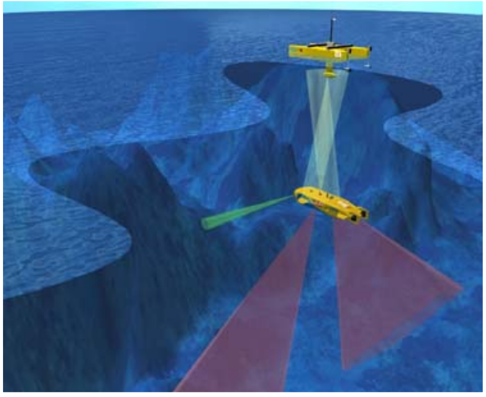

Fig. 1 Synchronization of two vehicles for data gathering at sea.

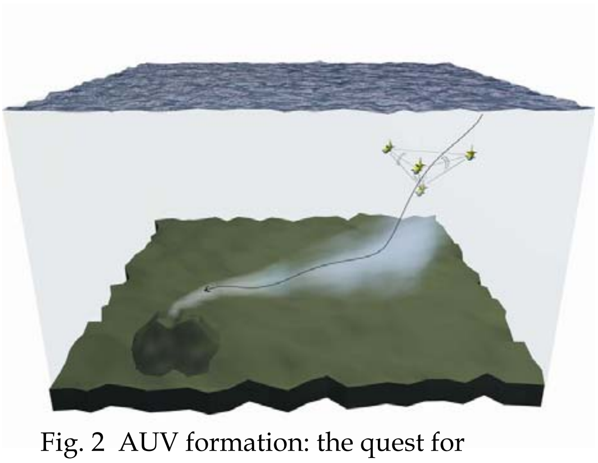

Fig. 2 AUV formation: the quest for hydrothermal vents

Figure 2 captures a different mission scenario involving a group of autonomous underwater vehicles (AUVs) in a "quest" for hydrothermal vents in the ocean floor. The mission is based on the knowledge that vents produce methane, which does not dissolve quickly in the water. This in turn allows for its detection and for the *measurement of the gradient of its concentration using methane sensors*. The vehicle baseline configuration is such that spatial estimates of the gradient of the methane concentration can be computed cooperatively. It is up to the fleet to maneuver so as to seek the region of higher concentration, and thus the localization of the vent. The scenario described requires multiple vehicle cooperation based on the type of information (methane concentration) that is acquired as the mission progresses. The mission poses formidable challenges to systems designers due to the need to develop a distributed, multi-vehicle cooperation scheme (requiring robust vehicle localization, navigation, and control) in the presence of severe underwater communication constraints. Other challenging scientific mission scenarios in the marine field can of course be envisioned (Cardigos et al., 2006).

Figure 3 shows the systems that are at the core of multiple vehicle cooperation. The scheme depicted is quite general and captures the basic trends in current research. Each vehicle is equipped with a *navigation and control system* that uses local information as well as information provided by a subset of the other vehicles over the communication network, so as to make the vehicle maneuver in cooperation with the whole formation.

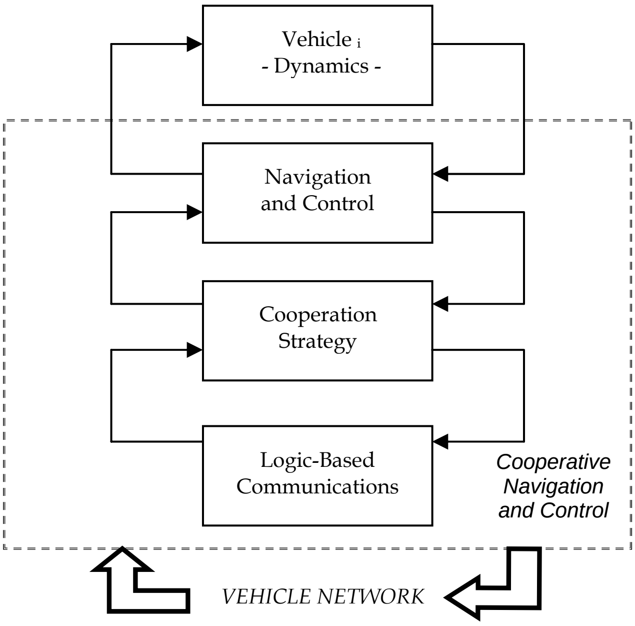

Fig. 3 General architecture for multiple vehicle cooperation

Navigation is in charge of computing the vehicle's state (e.g. position and velocity). Control accepts references for selected variables, together with the corresponding navigation data, and computes actuator commands so as to drive tracking errors to zero. The *cooperation strategy* block is responsible for implementing *cooperative navigation and control*. Its role is twofold: i) for *control* purposes, it issues high level synchronization commands to the local vehicle based on information available over the network (e.g. speed commands to achieve synchronization of a number of vehicles executing path following maneuvers). For *navigation* purposes, it merges local navigation data acquired with the vehicle itself as well as by a subset of the other vehicles. This is especially relevant in situations where only some of the vehicle can carry accurate navigation suites, whereas the others must rely on less precise sensor suites, complemented with information that is exchanged over the network. Finally, the system named *logic-based communications* is responsible for supervising the flow of information (to and from a subset of the other vehicles), which we assume is asynchronous, occurs on a discrete-time basis, has latency, and is subject to transmission failures. Central to the above scheme is the fact that each vehicle can only exchange information with a subset of the remaining group of vehicles. Furthermore, and because of the intrinsic nature of the underwater communications channel, communications should be parsimonious and take place at a very low data rate. This calls for the implementation of schemes to decide when and what minimum information should be transmitted from each of the vehicles to its neighbours. Interestingly enough, analogous constraints appear in the vibrant area of networked control systems, from which interesting and fruitful techniques can be borrowed.

Close inspection of the general architecture for multiple vehicle cooperation described above reveals the plethora of problems that must be addressed and solved:

i) Cooperative Control (CC) (e.g. cooperative path following and cooperate trajectory tracking),
ii) Cooperative Navigation (CN), and
iii) CC and CN under strict communication constraints over a faulty, possibly switching network.

From a theoretical standpoint, much work remains to be done to derive analysis and synthesis tools aimed at assessing stability and performance of such a general scheme. In this respect, there are some very recent results that stand at the crossroads of control and information theory. These will probably shed some light into stability and performance limitations under constraints on the capacity of the communication channels involved. Finally, there is a need to bridge the gap between theory and practice by actually implementing selected sets of algorithms for cooperative navigation and control using prototypes of marine vehicles. Some of these issues are briefly discussed in the text below.

Cooperative control of multiple autonomous vehicles: state of the art and future challenging problems

The ever increasing sophistication of autonomous vehicles (AVs) is steadily paving the way for the execution of complex missions without direct supervision of human operators. A key enabling element for the execution of such missions is the availability of advanced systems for navigation and motion control of AVs. The past few decades have witnessed considerable interest in this area (Fossen, 1994; Leonard, 1995; Encarnação and Pascoal, 2000; Alonge et al., 2001; Jiang, 2002; Pettersen and Nijmeijer, 2003; Aguiar and Hespanha, 2004; Aguiar and Hespanha, 2007a; Aguiar and Pascoal, 2007b). The problems of motion control addressed in the literature can be roughly classified into three groups: point stabilization, trajectory tracking, and path following. For underactuated AVs, motion control is still an active research topic (Aguiar and Hespanha, 2007a). The dynamics of these vehicles are nonlinear, which makes the control design task quite challenging. A common practice to deal with this issue is to simplify the dynamics using linearization-based techniques (Silvestre et al., 2002). The key assumption is that the range of operation is restricted to a small region for which the linear model remains valid. As a consequence, adequate control is only guaranteed in a neighborhood of the selected operating points and performance can suffer significantly when the required operating range is enlarged. Nonlinear Lyapunov-based designs can overcome some of the limitations mentioned above. See for example (Leonard, 1995; Encarnação and Pascoal, 2000; Alonge et al., 2001; Jiang, 2002; Pettersen and Nijmeijer, 2003)). Recently, in (Aguiar and Hespanha, 2007a) (see also (Aguiar et al., 2003) for experimental results conducted at Caltech) the authors have derived control algorithms for motion control of AVs (land and marine vehicles, in two and three-dimensional space). The important common feature that these designs share is the fact that they explicitly exploit the physical structure of the AVs instead of "fighting" it. In (Aguiar et al., 2007c), a robust control strategy called switched seesaw control is proposed that solves the challenging problem of point stabilization for a class of AVs in the presence of input disturbances and measurement noise.

Current research goes well beyond single vehicle control. In fact, recently there has been widespread interest in the problem of coordinated motion control of fleets of AVs. Applications include aircraft and spacecraft formation flying control (Beard et al., 2001; Giuletti et al., 2000), coordinated control of land robots (Desai et al., 2001), and control of multiple surface and underwater vehicles (Encarnação and Pascoal, 2001; Ögren et al., 2004; Skjetne et al., 2003; Skjetne et al., 2004, Pascoal et al., 2006; Ghabcheloo et al., 2006a; Ghabcheloo et al., 2006b; Aguiar and Pascoal, 2007d; Almeida et al., 2007). The concept of multiple AVs cooperatively performing a mission offers several advantages (over single vehicles working in a non-cooperative manner) such as increased efficiency, performance, reconfigurability, robustness, and the emergence of new capabilities.

The work reported in the literature is by now quite vast and addresses a large class of topics that include, among others, leader/follower formation flying, control of the "center of mass" and radius of dispersion of swarms of vehicles, and reaching a moving formation pattern. See for example (Rein et al., 2007) and the references therein. In the latter case, the goal is for the vehicles to achieve and maintain desired relative positions and orientations with respect to each other, while evolving at a desired formation speed. Central to the problems stated is the fact that each vehicle can only exchange information with a subset of the remaining group of vehicles. Similar constraints appear in the area of networked control (Hespanha et al., 2007).

The problem of coordinated motion control has several unique aspects that are at the root of new theoretical problems. As pointed out in (Fax and Murray, 2002) the following are worth stressing:

i) except for some cases in the area of aircraft control, the motion of one vehicle does not directly affect the motion of the other vehicles, that is, the vehicles are dynamically decoupled; the only coupling arises naturally out of the specification of the tasks that they are required to accomplish as an ensemble.

ii) there are strong practical limitations to the flow of information among vehicles, which may often be severely restricted due to the nature of the underlying communications network. In marine robotics, for example, underwater communications rely on the propagation of acoustic waves which travel at an approximate speed of 1500[m s^{-1}]. As is well known, this fact sets tight limitations on the communication bandwidths that can be achieved and introduces unavoidable latencies that depend on the distance between the emitter and the receiver (Pascoal et al., 2000). Thus, as a rule, no vehicle will be able to communicate with the entire formation. Furthermore, a reliable vehicle coordination scheme should exhibit some form of robustness against certain kinds of vehicle failures or temporary loss of inter-vehicle communications.

The coordination of AVs involves the design of distributed control laws with limited and disrupted communication, time-delays, model uncertainty, external disturbances, and possibly partial noisy state measurements. This is particularly significant in the case of underwater vehicles. It was only recently that these subjects have started to be formally tackled (see, e.g., (Beard et al., 2001; Giuletti et al., 2000; Ghabcheloo et al., 2006b; Borhaug et al., 2006)), and considerable research remains to be done to derive multiple vehicle control laws that can yield good performance in the presence of severe communication constraints. In (Ghabcheloo et al., 2006b), the concept of brief instabilities is exploited to model network failures and a distributed control law that ensures stability of a formation of autonomous marine vehicles is proposed The results of a simulation with this control law are shown in Fig. 4. Further work is required to address the problems of robustness against communication delays and to develop strategies that can decide at each instant of time whether or not it is worth sending data through the network. Preliminary results in this direction can be found in (Aguiar and Pascoal, 2007d), which describes how a logic-based communication system that bears affinity with some of the ideas exposed in (Hespanha et al., 2007) can be incorporated in each of the vehicles. This system effectively decides when to transmit information to the neighbors by comparing its actual state with its estimate, "as perceived" by the neighboring system, and transmitting data when the "difference" between the two exceeds a certain level.

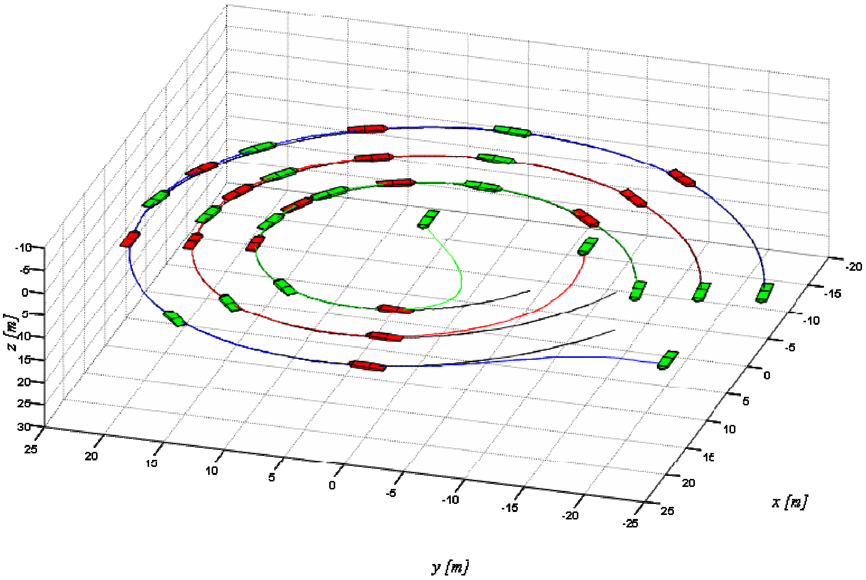

Fig. 4 Coordinated path-following of 3 AUVs under communication constraints

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