COORDINATED CONTROL OF AGENT FORMATIONS IN UNCERTAIN, DYNAMIC ENVIRONMENTS

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Abstract

This paper describes a framework for the motion co-ordination of networked vehicle systems. This framework is grounded on the UC Berkeley experience in the design, implementation and demonstration of control and communication systems for networked vehicles for land, sea and air applications. In this process we have developed a perspective on bringing together technological developments, theoretical underpinnings, and computational tools for the design and implementation of networked semiautonomous and autonomous vehicles. The motion co-ordination of independent modules that form the Mobile Offshore Base is used as a case study to pinpoint some general characteristics of vehicle formations. A classification of vehicle motion control problems is presented with emphasis on the properties of networked vehicle systems that are useful in our framework. The framework is then developed in terms of agent formations, and organisation of agent formation control encompassing trajectory generation for agent formations, stability and control of individual agents, and supervisory control.

1 Introduction

The University of California, Berkeley and California PATH have considerable experience in dealing with the co-ordinated control of vehicle formations, including automated highway systems and platoons of cars [7,13], helicopter formation flying [10], communication systems [2], and mobile offshore platforms [6]. Arguably the most salient similarity of these systems is the experimental validation of co-ordinated motion control systems and concepts. This similarity entails early prototyping, simulation and testing and interdisciplinary teams. This, in turn, entails the development of conceptual control architectures for each case. We have identified common design patterns for all these applications and we are now attempting to develop a uniform framework for the co-ordinated motion control of agent formations.

We will use the Mobile Offshore Base (MOB) as a case study and example throughout the paper. A Mobile Offshore Base is formed of several independent modules that are aligned to form a runway in the ocean. The alignment is maintained through the use of thrusters, connectors, or a combination of both. An automatic control system is used to maintain the position and the orientation of the base once stationed, to move the whole base from place to place, as well as to orient the assembly in the direction of the wind. The randomness and variability of the ocean environment render the problem difficult.

This problem will be used to illustrate our approach to the control of co-ordinated agent formations. Section two discusses the most salient issues of the MOB project. Section three will deal with a classification of different multiple agent co-ordination problems, and will situate the present work in the more general context of multi-agent systems. The notion of agent formation is presented in section four and defines the problems tackled in our framework. Section five details the framework we have developed for the coordinated control of agent formations. The notion of coordinated stability is discussed in section six. It is shown that the coordinated stability is highly dependent on the trajectory generation strategy that is chosen. Section seven deals with supervisory control techniques. Conclusions are drawn in section seven.

2 Case Study: The Mobile Offshore Base

The concept of a floating, at-sea base stems from the necessity for the United States to be able to stage military and/or humanitarian operations in any part of the world [14].
The Mobile Offshore Base is a very large floating ocean structure meant to provide the same capabilities as an on-land army base. It must be 1.5 miles long and accommodate the landing and take-off of C-17 conventional aircraft, host 3000 troops, carry 10 million gallons of fuel and provide 3 million square feet of internal configurable storage.

A single module cannot realistically provide the capabilities required for a MOB. No shipyard in the world can build structures this large. Moreover, the structure would be submitted to formidable loads in the ocean environment. Several designs were considered for the MOB project, which all include forming the MOB with several modules, kept aligned by thrusters, connectors, or a combination of both. The modules forming the MOB must be able to perform long-term station keeping at sea, in the presence of waves, winds and currents. This is traditionally referred to as Dynamic Positioning (DP) control [9,3].

The marine industry has experience with building dynamic positioning systems for a single ship [9]. In fact, DP systems are used extensively for oil drilling vessels, cable laying and inspecting, etc… However, the coordinated DP of several structures or ships with respect to one another has not received much attention. One possible reason is the sheer difficulty of the task. The ocean environment is highly variable, and first-order wave disturbances are hard to counteract. The unprecedented size and stability of the MOB makes it an ideal testbed for the development of robust coordinated DP control techniques.

But the modules composing the MOB are required to perform additional operations. These include:

- Assembling at sea,
- Remaining aligned and assembled to allow for landing of aircraft and cargo transfer from ships,
- Aligning in the wind to facilitate the landing of aircraft,
- And disassembling if the environmental conditions become to severe or in case of emergency.

It is anticipated that the MOB will transition/switch between several modes of operation as are follows:

- Unassembled mode: each individual module maintains a prescribed position and orientation.
- Assembled mode: the MOB assembly maintains a general position and orientation, and the individual modules maintain relative positions and orientations.
- Transitioning modules: independent modules are in preparation for mechanically connecting/disconnecting the modules end-to-end. Each transitioning mode corresponds to some prescribed sequence of operations. There are two major transitioning modes: the normal mode where the assembling and disassembling operations are executed one platform at a time, and the emergency mode, where disassembling is executed as fast as possible under survival conditions.

The breadth of potential applications for this manoeuvring technology has significantly increased the interest in this multi-disciplinary technology. Applications range from cargo transfer between ships (with special interest to logistic fleets), to thruster-assisted mooring and automated docking.

The Mobile Offshore Base can be viewed as a string of modules that have to be kept aligned. All modules are homogeneous, that is they are assumed to have the same dynamics and properties. It is possible to have heterogeneous agents within the MOB. Ships can position themselves side by side with the MOB for transfer cargo. Another case in which we have heterogeneous agents in the MOB is if we have a major failure in one of the modules, for instance if all thrusters fail on one platform. Limited operations can still occur by having the functioning modules follow the one with the failures. If two of the modules have major failures, the MOB ceases to be functional and some of its modules must separate. We need to reconfigure the string dynamically if problems arise, such as if all thrusters of a given module fail.

The most significant requirement is that the modules have good relative position control with respect to each other. The relative position requirements are quite tight. The (very large, very slow) modules must be within +/-5 meters of each other in the sway and surge directions, and within +/-1 degree of relative alignment, in disturbances up to sea state 6 (5-meter significant wave height, 17 m/s wind, 1 m/s currents). The string, however, is allowed to drift in terms of its global position. This allows for a reduction in the power consumption (cost) in lower sea states, and focuses all the control effort on maintaining the relative alignment in high sea states. The environment in which the modules “live” (the ocean) is assumed to be unconstrained, that is at this time we do not envision obstacle avoidance other than collision prevention between modules.

Because of the relatively slow dynamics of the modules, it was assumed that communication constraints between modules would be met at all times. Also, it is assumed that each platform has enough computational power to supervise all other platforms if needed.

The coordinated control problem for the MOB was separated into two hierarchical layers, the reference trajectory generation (higher level) and coordinated control strategies (lower level). The trajectory generation level deals with selecting a string control strategy, maximizing the string alignment, and minimizing the global fuel consumption. The coordinated control level deals with the implementation of a string control strategy, and the stability and control of neighbouring modules with respect to one another.

Hence, an important question that arose during the MOB project was that of the generation of reference points or trajectories for the modules. The approach that was adopted allows for the generation of either desired set points or trajectories for each module. A coordinated high-level controller generates the desired references. Several string control strategies have been studied in the MOB project,
including first-as-leader, middle-as-leader and leaderless approaches. As shown in [6], the choice of string control strategy affects the string stability for the coordinated system. Intuitively, a string of vehicles (such as a MOB or platoon of cars) is stable if errors do not amplify down the string. In terms of coordinated control, several approaches have been tested in this project, including PID control, sliding mode control and model predictive control strategies. The interested reader can find a description of Coordinated Dynamic Surface Control (DSC) for the MOB in [4,6].

3 Problem Taxonomy

A major difficulty in the study of the coordinated motion of multi-agent systems is the size of the space of possible configurations and designs problems. Our goal in this paper is not to provide a general classification procedure for multi-agent systems. We refer the interested reader to [1]. We simply wish to emphasize some characteristics of the types of problems that we have tackled. There are many definitions of agents. In this paper, “agent” is used to refer to a vehicle, such as the modules forming a MOB, the cars forming a platoon, the helicopters forming a platoon etc... The agents can have nonlinear dynamics, actuators or sensors. The agents evolve in a given environment. For our purposes this environment is not directly accessible (sensors are not perfect, do not cover the whole world), non-deterministic (agents may break, there is uncertainty), dynamic, and continuous. We are interested in agent formations, by contrast to problems in which all agents are independent. For our purposes the agents are organized in a particular geometrical configuration that defines the formation. Typical problems that arise are how to maintain the geometrical configuration and track desired changes of the configuration with time. These changes in the geometry of the formation are sometimes termed dynamic reconfiguration, meaning agents can be dynamically added or removed from the geometrical formation. Associated problems involve how to join and form the configuration, and how to separate from it. These different problems can be seen as modes of operation, and the switching between modes suggests the consideration of a hybrid system formalism. The dynamic nature of the problem stems from the existence of multiple vehicles whose roles, relative positions, and dependencies change during operations.

In the problems we have tackled, we have considered homogeneous agents that and have similar properties. By contrast, heterogeneous agent formations can also be considered. A question that arises in formations of multiple agents is that of whether the relative position of the agents in the formation is more important than the global position of the formation. In other words, should we privilege no collisions in the formation over exact position of the formation? The answer is problem specific and depends on what the goals and the constraints are for the formation. There are several types of agent constraints in these problems. We have assumed three main types of agent constraints: costs, computational requirements, and information requirements. Environmental constraints may also arise, such as in obstacle avoidance problems.

4 Agent Formations

We are concerned with multiple agent problems involving geometric patterns, for example multi-agent path planning, moving to and maintaining a formation and with the stability of coordinated motions are addressed in the description of the AHS. A one-dimensional geometry of agents is referred to as a string. A two or three-dimensional geometry is referred to as a mesh. An assembly of several agents is called a formation. The physical geometry of agents can be represented as a graph. There are numerous possible formations. The communications between agents can also be represented as a graph. In general both graphs are not identical. We are concerned with issues related to the modeling, design and implementation of networked vehicle systems. Formal models of hybrid systems, system architectures, hierarchical control architectures, the design of stable, robust coordinated controllers, and supervisory control are of concern. For simplicity, we are not addressing here the issues of complexity, dimension, control of emergent behaviors within control architectures, decentralization within a hierarchical architecture, functional coordination, and resource allocation.

5 The Framework

Control design for networked vehicle systems requires:
- Formal models that span the design and implementation processes.
- Frameworks where we can study the overall structure and properties of control designs that are not appropriately addressed within the constituent modules of the control architecture.
- Rigorous approaches to design and implementation.
- New control techniques.
These are the key elements of our framework.

A meticulous description of the control architecture for the MOB can be found in [5] and used as an example. The building blocks that form the architecture are modular and can be reused in all agent formation control problems. As discussed above, we organize the coordinated motion control into several hierarchical layers. The higher level generates either desired reference points or desired trajectory for the lower level control, which concerns itself with stability and trajectory tracking.
This higher level can itself be separated into several layers. The highest level is concerned with multi-agent path planning. In the case of the MOB, this layer picks an optimal alignment line for the modules, by minimizing fuel consumption and maximizing safety and efficiency. One level underneath, string control strategies decide how each module directly interacts with its neighbors (formation and marching problem). The string control strategies directly interact with the lower coordinated control strategy layer.

At the high level, we use techniques such as hybrid control design and verification, and protocol design and verification. At the lower level, we used coordinated control techniques.

6 String Control Strategies

Early in the University of California/PATH platooning [8] work it was noticed that strings of automatically controlled vehicles exhibited “string instabilities”, i.e., disturbances in the front of the platoon were amplified as they were propagated upstream. Ref. [11, 8, 12] showed through linear transfer function analysis that these instabilities could be eliminated by the introduction of a common reference trajectory for all of the vehicles. It was shown in Ref. [12] that if all of the vehicles in the platoon had knowledge of the lead vehicle’s absolute velocity then “weak string stability” could be achieved, i.e., no disturbance would ever be amplified as it traveled upstream in the platoon. It was also shown in [12] that if all of the vehicles in the platoon had knowledge of the relative position error between themselves and the lead vehicle, then “strong string stability” could be achieved, i.e., all downstream disturbances could be geometrically attenuated as they traveled upstream in the platoon. The lead vehicle information needs to be communicated to all of the vehicles via a communication link.

In the first scenario we considered, the first module in the MOB is considered the leader, and tracks an inertial reference. The second module tracks the first, the third module tracks the second one and so on. This is illustrated in figure 2. The gray arrows indicate inertial reference tracking, the pink arrows indicate the tracking of relative position of neighboring modules. This approach suffers from string instability [12]. Using the middle module as the leader reduces the instability by reducing the string length by half. Using a leaderless approach where each module tracks an inertial reference as well as its relative position to its neighbors solves the string stability problems and produces better overall alignment of the modules than the previous two strategies, as shown in [6].

7 Supervisory Control

In the MOB project, we investigated several supervisory control strategies. The current design is presented below.
Figure 3 shows a UML-compliant object-model diagram which specifies the classes of the supervision package and their structural relationship. The dispatcher is the central element of the supervisory control system. It takes its inputs from a user-written mission plan. The mission plan contains a list of parameterized commands. The dispatcher reads user-written commands from the mission plan, and translates them into elements that are comprehensible to the control system: maneuvers, and events. The numbers in the boxes indicate multiplicity information (instances): one dispatcher, one mission plan, one emergency maneuver can exist in the system. The "*" inside the maneuver and scheduled event blocks indicates that they can have unlimited instances.

A maneuver coordinates the motion of one or several modules; legal maneuvers are shown in figure 4. They include moving one module to a new position and heading, assembling modules to form a bigger MOB, separating assembled modules, moving a string of modules to a new position and heading, and rotating a string of modules into the wind.

Scheduled events are used in our framework to command a thruster failure, as shown in figure 5, so that we can simulate faults.

A special type of maneuver that the dispatcher can create is an "emergency maneuver". The dispatcher monitors the state of the MOB modules, and if "the news is not good", for example, if a collision is imminent, the emergency maneuver is initiated. In the current implementation, the emergency maneuver sets all thruster outputs to zero and the mission is aborted, but a more complicated scenario can be envisioned.
The dispatcher has four main modes (or states), as shown in figure 7. Upon initialization, the dispatcher enters the idle state. When the command to start a mission (start) is received, the dispatcher enters the dispatch state. It reads the first command in the plan, and, if it is a valid command, transitions to the execute maneuver state through the cmd_read transition. The dispatcher then creates a new maneuver. If there was already a valid maneuver, the system switches (gracefully) between maneuvers. The old maneuver is then destroyed. When a new maneuver presents itself, the dispatcher checks if the current maneuver has completed, and upon completion, creates the new maneuver, switches, and destroys the old maneuver.

8 Conclusions
This paper presents a framework for the coordinated control of agent formations in uncertain, dynamic environments. The Mobile Offshore Base program at the University of California, Berkeley is used as a case study throughout the paper. A taxonomy for this class of problems is provided, and the notion of agent formations is discussed. A rigorous framework is presented, and a discussion of issues related to the stability of agent formations and their supervisory control arises. This framework has been the backbone of the software development in the MOB program. It is currently being validated through a series of physical experiments on scaled MOB modules, conducted at Berkeley. Video from the physical experiments is available online at: http://path.berkeley.edu/~anouck/

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