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Formation Control of Multiple Autonomous Vehicle Systems

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This book is dedicated to:

My wife, Hong, and my children, Alan and Connie
–Hugh H.T. Liu

My wife, Qian Mo, and my parents, Genyi Zhu and Gengxin Zhang
–Bo Zhu

Contents

Preface

Background

Autonomous vehicles, or more precisely, autonomous vehicle systems, have received much attention from the public, thanks to well publicized products and product prototypes. Self-driving cars, drones and humanoid robots, are popular in exhibitions and shows. Some have even seen successful commercial applications. The smart, self-navigating iRobot^{TM} is no longer a curiosity from the research laboratory. Instead, iRobot products are already on the shelves of mainstream retailers, offering consumers their services, from vacuuming to mopping. In research and development, autonomous vehicle systems (AVSs) are receiving close attention, not only because of the wide range of their potential applications, but also because of the wide variety of vehicle configurations and platforms: cars, robots, spacecraft, and unmanned aerial vehicles (UAVs), to name just a few.

Even though different vehicle systems may have different configurations, they do share some common characteristics. For example, they must have some motion mechanism to enable movement; they are equipped with multiple sensory components to measure and collect vehicular and environmental information; they have "brains" (computer processors) to make automatic decisions to generate or regulate their motion based on the collected information, giving them a certain level of autonomy in accomplishing their missions. The enabling technologies behind these vehicles or vehicle systems – for example, the guidance, control and navigation technologies, the sensors and sensing technologies, and the communication protocols – represent state-of-the-art capabilities and highlight the current challenges and limitations in the field. Their capabilities and challenges make AVSs an exciting, almost ideal field to work in. As a result, AVSs have exhibited rapid progress in terms of research and development, from design to deployment.

Naturally, if we treat each vehicle as a self-regulating system, a fleet of vehicles will form a network of systems, or a system of systems. Such a macro viewpoint definitely broadens the horizon of AVSs to a new level. One may recognize the potential when a network of AVSs is considered. Imagine a single autonomous mobile robot is dispatched to survey and map a particular terrain, or an autonomous UAV flies over an area on an aerial photography mission: a coordinated group of mobile robots or a fleet of UAVs in formation can increase the scope of coverage dramatically. In another scenario, an individual robot or UAV has limited payload capacity, yet such tasks may be carried out by a team of cooperative robots or UAVs. In space applications, satellites stay in formation, to offer a wider coverage in telecommunications. Examples go on and on. If we group multiple autonomous vehicle systems together, we can significantly enhance performance and capacity, and multiple vehicle systems in coordination accomplish missions or tasks that a single vehicle cannot handle. The benefits are obvious.

We introduce a general term, *formation in motion*, for the phenomenon of multiple AVSs moving in coordination. One critical technology behind successful formation in motion is the control strategy that commands, coordinates, and adjusts the vehicles autonomously. As such, the *formation control of multiple autonomous vehicle systems* is the topic of interest to which this book is dedicated.

Contents of the Book

First of all, let us clarify what "formation control" or "formation in motion" refers to in this book. The concept of formation in motion can be intuitively described as a group of vehicle systems in motion that stays in a fixed pattern (e.g. a geometric shape). We may extend the concept to allow these vehicles to follow a dynamic pattern (e.g. spinning in a geometric fashion). Accordingly, formation control refers to control actions that ensure the group of vehicles stays in fixed or dynamic formation during its movement. It is worth pointing out that formation control is relevant to several associated concepts, such as coordinated control and cooperative control. Coordination, by definition, refers to the the harmonious functioning of parts for effective results. Cooperative control is a more general term, to address control and communication mechanisms that work together for control of large-scale dynamic systems. It is obvious that formation control demonstrates distinctive features of shape-keeping and, by implication, of motion synchronization. In this book, we assume we are dealing with formation control unless otherwise specified.

Formation control of AVSs involves the dynamics and control aspects of the dynamic behaviour of multi-vehicle systems, the design of proper control techniques to regulate the formation motion of these vehicles, and the development of system-level decision-making strategies to increase the level of autonomy for the whole group of vehicles, enabling them to carry out their missions. The fundamental concepts of dynamics and control are the main focus presented in this book. Formation control involves communication protocols, network frameworks, and information technology. Covering these associated technologies goes beyond the scope of this book, but the relevant concepts will be introduced at suitable points in the text.

In terms of dynamics, attention is focused on multi-vehicle systems dynamics. The intention is to develop a uniform paradigm for describing vehicle systems' dynamic behaviour, addressing both individual vehicle motion and overall group movement. Interactions between vehicles are also covered. Considering various vehicle configuration possibilities and even heterogeneous vehicles, it is important to have a unified platform so as to provide a foundation for analysis.

Similarly, regarding control, the intention is to focus on formation control, in other words the control strategy and its implementation in each individual vehicle so that it remains in fixed or dynamic formation while in motion. We shall cover fundamental

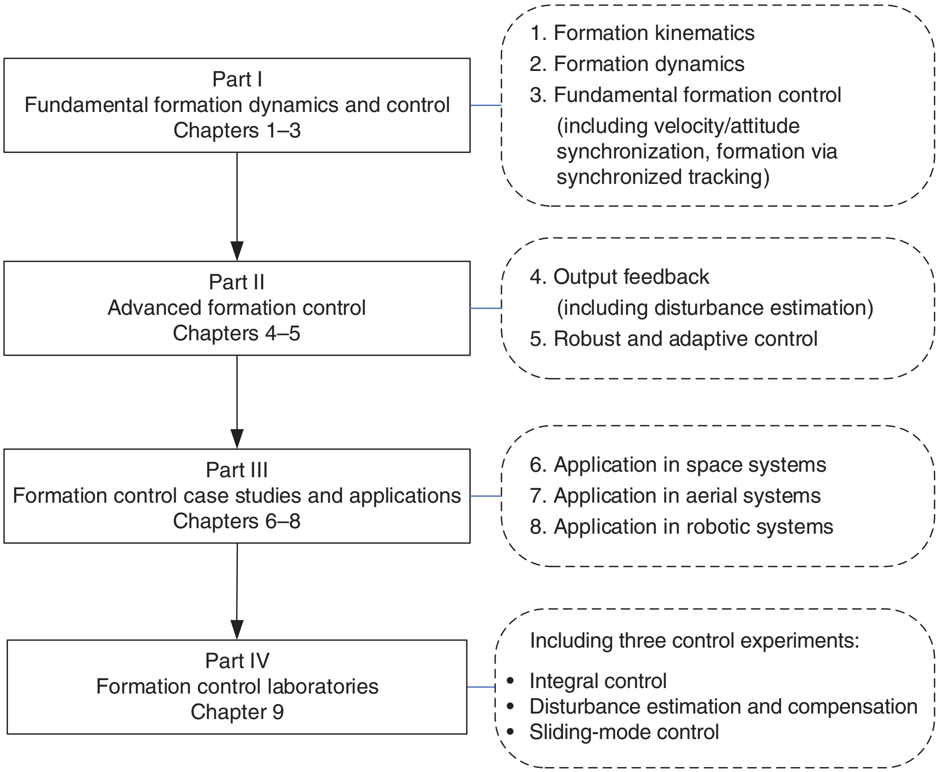

Figure 1 The roadmap of the book.

formation control concepts, as well as more advanced topics relating to special cases or applications.

In addition, several formation control application case studies are presented in this book. These cases cover descriptions, design, and control of different vehicle systems, including robotics, space applications, and UAVs. A dedicated section covers design of laboratory experiments. These exercises will give readers opportunities to further enhance their learning experience.

The roadmap of the rest of the book is shown in Figure 1.

After the Preface, the rest of the book is organized into four parts and nine chapters. Part I covers the fundamental topics, including vectorial formation dynamics (Chapter 2) and fundamental formation control (Chapter 3). Part II addresses advanced topics, including output feedback formation control (Chapter 4) and robust and adaptive formation control (Chapter 5). Part III focuses on formation control application case studies in a wide range of areas. Chapter 6 describes formation control for space systems, Chapter 7 presents formation control for aerial systems, Chapter 8 describes formation control for robotic systems. Part IV presents a unique laboratory, a system of three degree-of-freedom (DOF) desktop "helicopters", which is an excellent platform to investigate formation dynamics and control issues experimentally.

Curriculum

As mentioned before, in this book, we focus on specific formation behaviours and explore a unified dynamic behaviour description with various formation control strategies. The book is intended to be used as a textbook for a graduate-level course. It can certainly serve as a reference book or textbook for a senior undergraduate course. In North America, a standard graduate course for one semester typically consists of 2-hour lectures. A suggested course syllabus is provided in Table 1 as the recommended template for the course delivery.

Table 1 Suggested syllabus.

Week	Topic	Lab work
1	Chapter 1: Introduction	
2	Chapter 2: Formation Dynamics	
3	Chapter 2 (cont'd)	Lab: 3DOF modelling
4	Chapter 3: Fundamental Formation Control	
5	Chapter 3 (cont'd)	Lab: 3DOF Control
6	Chapter 4: Output Feedback	
7	Chapter 5: Robust and Adaptive Formation Control	Lab: 3DOF Advanced Control
8	Chapter 6: Space Systems	
9	Chapter 7: Aerial Systems	Lab: 3DOF UAV Control
10	Chapter 8: Robotic Systems	
11	Course Review	
12	Laboratory Project Demonstration	
13	Exam	

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