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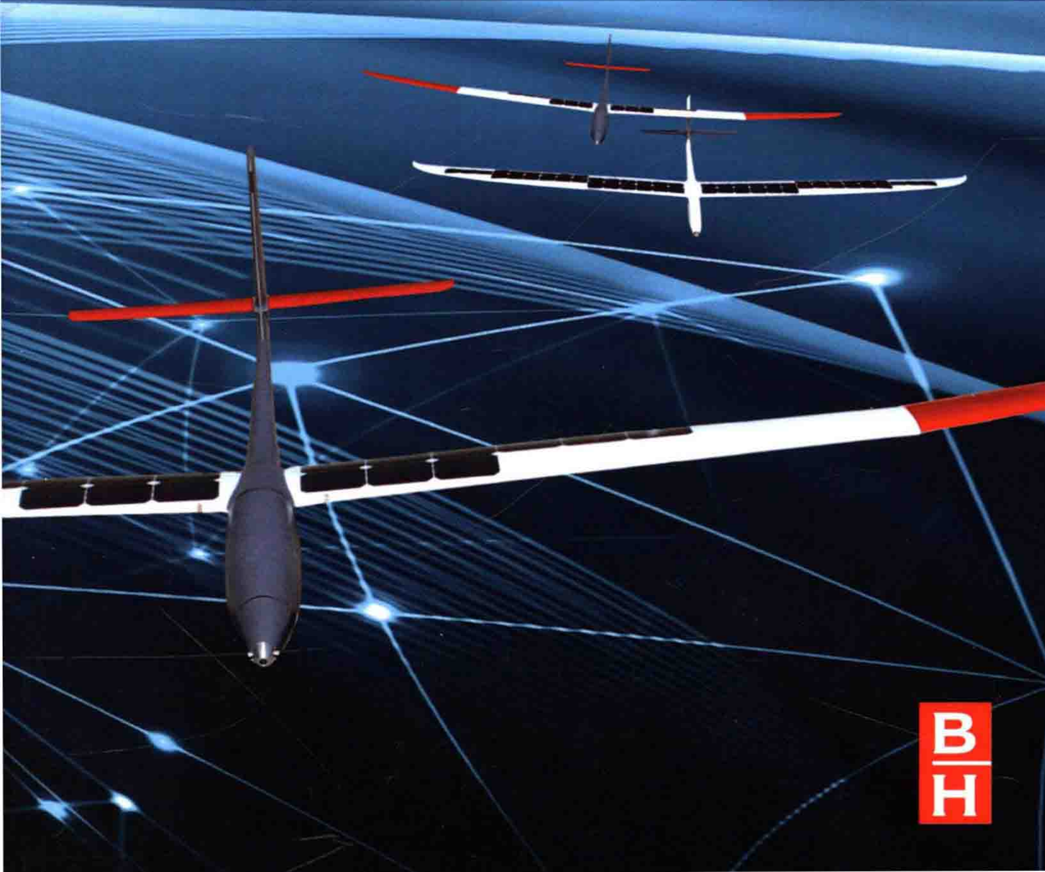

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The advent of powerful embedded systems and communications networks has spawned widespread interest in the problem of cooperative motion control of multiple autonomous vehicles that will be engaged in increasingly demanding scientific and commercial missions.

Time-Critical Cooperative Control of Autonomous Air Vehicles presents a theoretical framework that addresses new and challenging multiple vehicle mission requirements, yielding control strategies for temporal coordination of networked autonomous agents that are subjected to tight spatial constraints.

The book gives the reader a thorough, integrated presentation of the different concepts, mathematical tools, and networked control solutions needed to tackle and solve a number of problems in the general area of time-critical cooperative control. In particular, it integrates algorithms for path following and time-critical coordination that together give a team of unmanned air vehicles (UAVs) the ability to meet simultaneously desired spatial and temporal specifications.

By including case studies in the control of fixed-wing and multirotor UAVs, the book effectively broadens the scope of application of the methodologies developed. The theoretical presentation and simulations are complemented with the results of actual flight tests with real UAVs.

This book is intended for researchers and practitioners from academia, research labs, commercial companies, government agencies, and the international aerospace industry.

About the authors

Isaac Kaminer received his PhD in Electrical Engineering Systems in 1992 from the University of Michigan, MI, USA. He is a Professor at the Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA, USA

António Pascoal received his PhD in Control Science in 1987 from the University of Minnesota, Minneapolis, MN, USA. He is an Associate Professor of Control and Robotics at IST, University of Lisbon, Portugal and a Senior Researcher at the Institute for Systems and Robotics-Lisbon. He is also an Adjunct Scientist with the National Institute of Oceanography (NIO), Goa, India.

Enric Xargay earned his PhD in Aerospace Engineering in 2013 from the University of Illinois, Urbana, IL, USA. He is Cofounder and Director of CSTAR Pte Ltd, a company that focuses on the development of guidance, navigation, and control technologies for autonomous systems.

Naira Hovakimyan received her PhD in Physics and Mathematics in 1992, in Moscow, from the Institute of Applied Mathematics of the Russian Academy of Sciences, in the area of optimal control and differential games. She is currently a W. Grafton and Lillian B. Wilkins Professor of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign.

Venanzio Cichella received his BS and MS degrees in Automation Engineering in 2007 and 2011, respectively, from the University of Bologna, Italy. He is currently a PhD student in Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign.

Vladimir Dobrokhodov received his PhD in Aerospace Engineering in 1999, from the Zhukovsky Air Force Engineering Academy of the Russian Academy of Sciences in Moscow, in the area of aircraft flight dynamics and control. He is currently an Associate Professor at the Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA, USA.

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Time-Critical Cooperative Control of Autonomous Air Vehicles

To the precious memory of my mother Olga and grandmother Leah,
to my father Isaac, to my sons Emanuel and Conor,
to Jenny, Cristof, and Shoshi and to Ekaterina, my love.

Isaac Kaminer

To the beloved memory of my parents Manuel and Idalina,
to my wife Stephanie and son Ricardo with boundless love and gratitude.

António Pascoal

To my parents, Elvira and Enric, with admiration, gratitude,
and unconditional love.

Enric Xargay

To the children: Arik, Arsen, and Maria with all my love, with all my heart.

Naira Hovakimyan

To my grandfather Ferruccio,
to the loving memory of my grandparents Gina, Giovanna, and Venanzio,
always present in my thoughts, in my heart, in my life.

Venanzio Cichella

To my parents, Valentina and Nicholai, with gratitude and admiration,
to my girls Elena and Anna who are the purpose of my life,
and to my brother Oleg who is always there for me.

Vladimir Dobrokhodov

Foreword

We can see on the horizon a new age of autonomous systems in which the opportunities for applications are endless: self-driving cars and trucks, autonomous package and cargo delivery systems, police and military operations, earth exploration, critical infrastructure inspection and maintenance, and medical diagnostics and operating room robotics, to name a few. Autonomous systems with machine reasoning and intelligence will forever change how machines serve humans. We are at the threshold of an era when humans and machines understanding mission context, sharing understanding and situation awareness, and adapting to the needs and capabilities of each other with advanced communication systems, control algorithms, and sensor networks will execute challenging scientific and commercial missions with unprecedented safety, reliability, and performance.

Control theory brings together advanced mathematics, modeling and simulation, and software development, and forms the kernel for the operating systems embedded in autonomous systems. Control of multiple autonomous air vehicles is one of the most challenging control problems due to the nature of flight. Each air vehicle control and mission management system consists of nested control loops which must provide inner-loop stability, command following, and outer-loop trajectory control to accomplish demanding tasks, as well as have the ability to reject/compensate for significant environmental disturbances. The resulting architecture must manage tasks, generate trajectories, enable vehicles to follow the corresponding paths, perform under failures, damage, or when things go wrong, and communicate critical information to all systems that need it.

This book represents a welcome contribution to the literature on the development of autonomous systems. It addresses key topics that are critical to the control of autonomous air vehicles and provides a rigorous mathematical formulation for control systems design and analysis. Clearly, having multiple air vehicles cooperate to execute complex missions requires the ability to follow desired paths and complete tasks at prescribed times, and to be able to do this under limited/constrained communications networks. The authors Isaac Kaminer, António Pascoal, Enric Xargay, Naira Hovakimyan, Venanzio Cichella, and Vladimir Dobrokhodov bring together a wealth of experience and theoretical rigor applied to the time-critical control of autonomous fixed-wing and multirotor air vehicles. The first section of this book gives an overview of a general framework leading to an architecture for trajectory generation, path following, multi-vehicle coordination and communications, and inner-loop autopilot control. The key idea exploited is the decoupling of space and time that allows using the velocities of the vehicles for coordination, while circumventing the performance limitations of trajectory tracking controllers. This decoupling makes it possible to account for heterogeneous vehicle dynamics. The second and third sections use the framework proposed to address time-critical control of autonomous fixed-wing and multirotor air vehicles under very general assumptions on the topology of the underlying communications network. They also provide detailed algorithm development, implementation details, and simulation examples that arise in the course of representative mission scenarios. For the missions described, both relative and absolute temporal constraints are considered. The mathematical machinery adopted to study networked cooperative systems allows for the consideration of challenging issues such as quantization in information sharing and low-connectivity in networks. Flight tests of cooperative road search using fixed-wing UAVs and coordinated flight of multirotors are used to illustrate the theoretical results. By bringing together theory and practice, this book affords researchers and practitioners in the field of cooperative air robotics a solid foundation to develop further theoretical work and pursue the implementation of new methodologies. Both control system academics and aerospace engineers will find the presentation intriguing, illuminating, and inspiring.

Kevin A. Wise
Senior Technical Fellow, Advanced Flight Controls
The Boeing Company

February, 2017

Preface

The advent of powerful embedded systems and communications networks has spawned widespread interest in the problem of coordinated motion control of multiple autonomous vehicles that will be engaged in increasingly challenging mission scenarios. The types of applications considered include, but are not limited to, intelligent surveillance and reconnaissance, environmental monitoring, and data collection by exploiting tools available for networked control of multiple heterogeneous autonomous robots. The latter include air, land, ocean-surface, and underwater vehicles. This book focuses on autonomous air vehicles. However, the tools developed for multiple vehicle coordination are sufficiently general to be extended and applied to the control of other kinds of autonomous platforms. A large subset of the missions proposed for air vehicles requires that they coordinate their motion in relative but not necessarily absolute time. For example, in a rendezvous mission, the times of arrival of the vehicles at their destinations may be required to be the same, but not specified a priori. To meet the requirements imposed by these types of applications, a new control paradigm must be developed that departs considerably from classical control strategies. To this end, this book details a theoretical framework for cooperative autonomous air vehicle control that addresses explicitly new and challenging temporal mission specifications, together with stringent spatial constraints. In particular, the framework integrates algorithms for path following and time-critical coordination that together provide a team of Unmanned Air Vehicles (UAVs) with the ability to meet joint spatial and temporal assignments.

The key contribution of this book is the development of a *cooperative path-following framework* that addresses explicitly time-critical issues. In its essence, the cooperative strategy proposed consists of assigning each vehicle a feasible path that satisfies mission requirements and vehicle dynamic constraints and then having each vehicle follow its assigned path while coordinating its position along that path with the other vehicles in the team. This is accomplished by judiciously decoupling space and time in the formulation of the trajectory-generation, path-following, and time-coordination problems. The result is a systematic framework for integration of various tools and concepts from a broad spectrum of disciplines leading to a streamlined design procedure accessible to a typical control engineer.

The book is organized in four parts with a total of twelve chapters. Two appendices that review the necessary mathematical background and contain proofs of the main theoretical results are also included. The organization of the different parts and chapters is detailed next:

- **Part I** introduces the framework for multiple vehicle cooperation adopted in the book and discusses a set of multi-vehicle mission scenarios that warrant the implementation of the proposed control architectures.

- **Chapter 1** affords the reader a general description of the problems addressed in the book and how they relate to previous work reported in the literature. The chapter describes the practical motivation for the topics considered and includes two illustrative UAV mission scenarios: cooperative road search and sequential auto-landing.
- **Chapter 2** formulates the problem of time-critical cooperative path-following control of multiple UAVs in 3D space. The chapter introduces also a set of assumptions and constraints on the supporting communications network as well as on the autopilots mounted onboard the UAVs.

- **Part II** presents the cooperative path-following control framework for fixed-wing UAVs.

  - **Chapter 3** formulates the problem of path-following control for a single UAV, and describes a nonlinear control algorithm that uses angular rates to steer the vehicle along a 3D spatial path for an arbitrary feasible speed assignment along the path.
  - **Chapter 4** presents a strategy for time coordination of multiple UAVs, yielding a framework for cooperative path following. The strategy proposed relies on the adjustment of the speed profile of each vehicle based on coordination information exchanged over the inter-vehicle communications network. In particular, a set of coordination states and coordination maps is proposed that allows for the application of the cooperative path-following framework to the case of path-dependent, desired speed profiles.
  - **Chapter 5** extends the coordination control law presented in Chapter 4 to support time-critical multi-vehicle missions that impose absolute temporal constraints on the trajectories of the vehicles, in addition to relative temporal assignments. The chapter addresses cooperative missions that require the vehicles to strictly observe absolute temporal specifications, as well as missions that only require the fleet to coordinate within a desired temporal window.
  - Motivated by the use of networks with finite-rate communication links, **Chapter 6** analyzes the effect of quantization on the stability and convergence properties of the closed-loop coordination dynamics. The results in this chapter show that, depending on the design of the quantized coordination control law, the closed-loop coordination error dynamics have undesirable "zero-speed" attractors. A modification of the coordination control law presented in Chapter 4 is proposed that retains the origin as the only equilibrium point of the system and prevents the existence of "zero-speed" equilibria.
  - **Chapter 7** proposes a modification of the coordination control law introduced in Chapter 4 with the objective of improving the convergence rate of the closed-loop coordination dynamics in low-connectivity scenarios. The proposed approach, which borrows and expands tools and concepts from the control of complex networks and logic-based communication protocols, leads to an evolving extended network, whose topology depends on the local exchange of information among vehicles.

- **Chapter 8** presents the results of flight tests for a cooperative road-search mission that show the efficacy of the multi-UAV cooperative framework. The results demonstrate the validity of the proposed theoretical framework in a specific realistic application as well as the feasibility of the onboard implementation of the algorithms developed.

- **Part III** extends the cooperative path-following control framework to multirotor UAVs.
  - **Chapter 9** presents a solution to the problem of path-following control for a single multirotor UAV. The strategy departs from the control law for fixed-wing UAVs described in Chapter 3 in that it is applicable to vehicles that may have a zero velocity vector at some point during the execution of the mission.
  - **Chapter 10** proposes a time-coordination algorithm that, similar to the one discussed in Chapter 4, relies on the exchange of coordination information over the inter-vehicle communications network. However, the different dynamics of multirotor vehicles require a different structure for the coordination control law, which now adjusts the acceleration profile of the vehicles along their corresponding paths, instead of their speed profile.
  - **Chapter 11** presents flight-test results of a team of multirotor UAVs executing time-critical cooperative maneuvers.

- Finally, **Part IV** concludes the book:
  - **Chapter 12** summarizes the current state of development of time-critical cooperative path-following control, identifies some important open problems that deserve further attention, and discusses the application of the proposed framework to present and future multi-vehicle missions.

Acknowledgments

This book is the natural consequence of many years of research by the authors in the general area of networked cooperative motion planning and control of autonomous vehicles. In this endeavor we were brought together by our common passion to bring theoretical results in control and networked systems theory to bear on the development of new practical-oriented methods for time-critical cooperative control of autonomous air vehicles. The writing of the book was in itself a distributed, cooperative process involving human "agents" working at different geographical locations. We hope the final outcome will be looked upon as a comprehensive framework for cooperative UAV control systems design and implementation, capable of inspiring new research and guiding practitioners in various applications of autonomous systems.

The work that we summarize in this book was strongly influenced by and benefited from close interaction with many colleagues, postdoctoral fellows, and graduate students that we were fortunate to meet in our paths. All of them contributed directly or indirectly to creating an extremely rich and motivating collective atmosphere that stimulated visionary thinking, open discussions, and the free interchange of ideas. Among those with whom we shared ideas and concepts, we owe a special word of gratitude to António Aguiar, Reza Ghabcheloo, João Hespanha, and Carlos Silvestre for early joint work on cooperative path-following and networked control under intermittent communication losses. We also owe much to the members, past and present, of the Advanced Controls Research Lab of the University of Illinois for having created and nurtured a pleasant and stimulating working atmosphere. Chengyu Cao deserves special mention for his contribution to the development of path-following control algorithms with $\mathcal{L}_1$ adaptive augmentation. Ronald Choe made significant contributions to our path-following and coordination control laws as he developed a novel framework for distributed cooperative trajectory generation. Javier Puig-Navarro played an important role in advancing the theory of time-critical coordination with absolute temporal constraints. We are also thankful to Dušan Stipanović and Petros Voulgaris for many useful discussions on the topic.

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