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Aerial Manipulation

Springer

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To my dear and patient wife Nives

M.O.

To my wife, Adriana

C.K.

To Jakov and Domagoj, my sons

S.B.

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new design philosophies…, new challenges. Much of this development work resides in industrial reports, feasibility study papers, and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Aerial manipulation is an "emerging technology" that although sounding futuristic undoubtedly has much potential for applications development. The material presented in this monograph is conceptual and theoretical but is also grounded in today's technology and hardware; there are rotorcraft applications presented in various sections of the monograph. The monograph focuses on a thorough presentation of basic concepts and physical principles, mathematical models, and demonstrations by worked examples. The chapter titles demonstrate quite clearly how the authors plan to advance the reader's understanding of the structure and operation of generic aerial manipulators:

Chapter 1 State of the Art; Chap. 2 Coordinate Systems and Kinematics; Chap. 3 Aerodynamics and Rotor Actuation; Chap. 4 Manipulator Kinematics; Chap. 5 Aerial Manipulator Dynamics; Chap. 6 Sensors and Control; Chap. 7 Mission Planning and Control.

Of particular interest to the control specialist, the topics of Chap. 6 include schemes for a modular structure of sensing and control tasks. There are some low-level control loops that use PID control and high-level control loops that use standard PID control. This chapter also introduces the sophisticated control methods of gain scheduling, model reference adaptive control (MRAC), and robust adaptive control to tackle more complicated system-operational issues.

The experienced authorial team comprises: Matko Orsag who is an Assistant Professor in the Laboratory for Robotics and Intelligent Control at the University of Zagreb, Croatia. He has spent time at the University of Drexel, USA, pursuing

robotics and UAV research. Christopher Korpela is an Academy Professor at West Point Military Academy, USA, and serves as Deputy Director of the Robotics Laboratory at that Institution. Stjepan Bogdan is a Full Professor, also on the academic staff of the Laboratory for Robotics and Intelligent Control Systems at the University of Zagreb. He was the lead author on the monograph *Manufacturing Systems Control Design* (ISBN 1-84628-982-9, 2006) published in the *Advances in Industrial Control* series. More recently, he has refocused his research on robotics and related autonomous systems. Finally, Paul Oh is Lincy Professor of Unmanned Aerial Systems at the University of Nevada, Las Vegas, USA. He has extensive professional experience of the aerial manipulator topic. Mention should also be made of Prof. Anibal Ollero, who is a distinguished Spanish scientist at the Escuela Técnica Superior de Igeniería at the University of Seville, Spain. He contributed the State-of-the-Art review found in Chap. 1.

This monograph *Aerial Manipulation* will be of considerable interest to researchers in the fields of robotics, aerospace, and control. Those researchers who are at postgraduate, postdoctoral, and faculty staff level will appreciate the conceptual presentation of the authors and may find inspiration for new projects. There may be some interest from final-year undergraduate students seeking novel project material. It is a fascinating subject, and it may be that "do-it-yourself" hobbyists in aerial systems and rotorcraft technology will find inspiration for practical projects from the monograph too.

The editors of the *Advances in Industrial Control* monograph series would be delighted to add further monographs describing the theory, laboratory research, and industrial applications in this interesting emerging field of robotic endeavor. Meantime, the authors are to be congratulated on producing a first volume on aerial manipulation for the *Advances in Industrial Control* series.

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Preface

As scholars we have the rare privilege to take part in the excitement that students feel when their thoughts and abstract mathematical forms are implemented on electrical-mechanical systems—motors start to spin, parts start to move, image processing reveals hidden features, the systems become 'alive'. No matter how many times we have witnessed those thrills, again and again these small "miracles" and students' passion make teaching and research so rewarding. And this is especially true for robotics that is considered likely to become one of the most influential technologies in the decades to come. Rapid development of electronics, emergence of new materials, and advances in computer science provide for the implementation of complex algorithms and structures that are capable of raising the cognitive and manipulative abilities of robots to a new level and introducing them into new fields.

One of these new fields of robotics is so-called aerial robotics—technology that provides services and facilitates the execution of tasks (such as observation, inspection, mapping, search and rescue, maintenance) by using unmanned aerial vehicles equipped with various sensors and actuators. While some of these services have already been put into practice (e.g., aerial inspection and aerial mapping), others (like aerial manipulation) are still at the level of laboratory experimentation on account of their complexity. The ability of an aerial robotic system to interact physically with objects within its surroundings completely transforms the way we view applications of unmanned aerial systems in near-earth environments. This change in paradigm conveying such new functionalities as aerial tactile inspection; aerial repair, construction, and assembly; aerial agricultural care; and aerial urban sanitation requires an extension of current modeling and control techniques as well as the development of novel concepts.

Working for more than ten years in the field, we have discerned the expeditious growth of scientific publications related to aerial robotics—special sessions and workshops have been organized as a part of major robotics conferences, leading journals in the field have published special issues on the topic, and aerial robotics competitions and challenges have been arranged. All this has been closely followed by articles for the general public aimed at the popularization of this new scientific

field and in the same time by the rise of hundreds of small companies eager to commercialize the latest findings. Even though far from being mature, aerial robotics slowly but surely is becoming a very important aspect in the creation of novel industries that will mark this century. This book is a modest attempt to provide an in-depth treatment of aerial manipulation—the most complex area of aerial robotics. Covering all the steps, from the physical basics of rigid body kinematics and dynamics through modeling of an unmanned aerial vehicle equipped with a dexterous manipulator to the description of aerodynamic phenomena associated with propulsion systems and the design of complex control compositions, this book is a sound foundation for a newcomer in the field and at the same time represents complementary material for researchers seeking to enhance expertise in the field of aerial manipulation.

Careful selection of the fundamental elements of rigid body dynamics and kinematics, as well as essential principles of aerodynamics, provides a well-balanced background for effective and efficient design of unmanned aerial manipulation systems. A systematic presentation of control techniques and aerial robotic systems control structures provides a blueprint for immediate implementation to real-world problems. Easy-to-follow exercises and examples offer students and researchers unique insight into the practice of modeling and control of aerial robotics systems.

We hope that our text will help in understanding the phenomena encountered in aerial robotics, thus eliciting exciting moments and encouraging engineering "miracles" in research laboratories and industrial facilities.

Zagreb, Croatia
December 2016

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Many individuals have contributed to this book. We are indebted to the students who contributed by performing some of the simulations and practical experiments while doing their student projects or working on their diploma and master theses. This list includes, in particular, Tomislav Haus, Antun Ivanovic, and Marko Car. We would like to thank Prof. Anibal Ollero, one of the leading experts in the field, for his support and willingness to participate as the author of the introductory chapter of this book.

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