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Marco Tognon · Antonio Franchi

Theory and Applications for Control of Aerial Robots in Physical Interaction Through Tethers

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Series Editor's Foreword

At the dawn of the century's third decade, robotics is reaching an elevated level of maturity and continues to benefit from the advances and innovations in its enabling technologies. These all are contributing to an unprecedented effort to bringing robots to human environment in hospitals and homes, factories and schools; in the field for robots fighting fires, making goods and products, picking fruits and watering the farmland, saving time and lives. Robots today hold the promise for making a considerable impact in a wide range of real-world applications from industrial manufacturing to healthcare, transportation, and exploration of the deep space and sea. Tomorrow, robots will become pervasive and touch upon many aspects of modern life.

The *Springer Tracts in Advanced Robotics (STAR)* is devoted to bringing to the research community the latest advances in the robotics field on the basis of their significance and quality. Through a wide and timely dissemination of critical research developments in robotics, our objective with this series is to promote more exchanges and collaborations among the researchers in the community and contribute to further advancements in this rapidly growing field.

The monograph by Marco Tognon and Antonio Franchi is the outcome of the first author's Ph.D. thesis on tethered aerial vehicles. The work comes at the intersection of two hot research areas, namely aerial robotics and robot physical interaction, and constitutes a valuable reference in the new field of aerial physical interaction. A number of controllers and observers are proposed to fully exploit aerial robots' capabilities to interact with the environment, and even a multi-tethered system composed of two aerial robots is considered.

The techniques are effectively implemented in a large number of simulated and experimental tests, including a significant use case, and the various results are keenly discussed. A very fine addition to the STAR series!

Naples, Italy
April 2020

Bruno Siciliano
STAR Editor

To beloved family and friends.

Preface

This book focuses on the study of autonomous aerial robots interacting with the surrounding environment, and in particular on the design of new *control* and *motion planning* methods for such systems. Nowadays, autonomous aerial vehicles are extensively employed in many fields of application but mostly as autonomously moving sensors used only to sense the environment. On the other hand, in the recent field of *aerial physical interaction*, the goal is to go beyond sensing-only applications and to fully exploit aerial robots capabilities in order to interact with the environment, exchanging forces for pushing/pulling/sliding, and manipulating objects. However, due to the different nature of the problems, new control methods are needed. These methods have to preserve the system stability during the interaction and to be robust against external disturbances, finally enabling the robot to perform a given task. Moreover, researchers and engineers need to face other challenges generated by the high complexity of aerial manipulators, e.g., a large number of degrees of freedom, strong nonlinearities, and actuation limits. Furthermore, trajectories of the aerial robots have to be carefully computed using motion planning techniques. To perform the sough task in a safe way, the planned trajectory must avoid obstacles and has to be suitable for the dynamics of the system and its actuation limits.

With the aim of achieving the previously mentioned general goals, this book considers the analysis of a particular class of aerial robots interacting with the environment: *tethered aerial vehicles*. The study of particular systems, still encapsulating all the challenges of the general problem, helps on acquiring the knowledge and the expertise for a subsequent development of more general methods applicable to aerial physical interaction. This work focuses on the thorough formal analysis of tethered aerial vehicles ranging from control and state estimation to motion planning. In particular, the differential flatness property of the system is investigated, finding two possible sets of flat outputs that reveal new capabilities of such a system. One contains the position of the vehicle and the link internal force (equivalently the interaction force with the environment), while the second contains the position and a variable linked to the attitude of the vehicle. This shows new control and physical interaction capabilities different from standard aerial robots in contact-free flight. In particular, the first set of flat outputs allows realizing one of the first “free-floating” versions of the classical hybrid force-motion control for standard grounded manipulators.

Based on these results we designed two types of controllers. The first is an easy-to-implement controller based on a hierarchical approach. Although it shows good performance in quasi-static conditions, actually the tracking error increases when tracking a dynamic trajectory. Thus, a second controller more suited for tracking problems has been designed based on the dynamic feedback linearization technique. Two observers, for the 3D and 2D environments, respectively, have been designed in order to close the control loop using a minimal sensorial setup. We showed that the tether makes possible to retrieve an estimation of the full state from only an IMU plus three encoders for the 3D case, while from just an IMU for the 2D case. Parts of those results were extended to a novel and original multi-robots case as well. We considered a multi-tethered system composed of two aerial robots linked to the ground and to each other by two links. The theoretical results on generic tethered aerial vehicles were finally employed to solve the practical and challenging problem of *landing and takeoff on/from a sloped surface*, enhancing the robustness and reliability of the maneuvers with respect to the contact-free flight solution.

This work has been supported by the European Union’s Horizon 2020 research and innovation programme under grant agreement No 644271 AEROARMS.

We would like to express our deep gratitude to Dr. Anthony Mallet for the excellent and continuous maintenance of the software and hardware framework. Without his precious work, the several experiments conducted during this work would not have been possible.

A sincere gratitude go to all the colleagues that contributed to this work: Sanket Dash, Andrea Testa, and Enrica Rossi.

Toulouse, France
February 2020

Marco Tognon
Antonio Franchi

Contents

Acronyms

ACADO	Automatic Control and Dynamic Optimization
AM	Aerial Manipulation
APhI	Aerial Physical Interaction
AR	Aerial Robot
AV	Aerial Vehicle
BLDC	Brushless DC
CoG	Center of Gravity
CoM	Center of Mass
DFL	Dynamic Feedback Linearization
DoF	Degree of Freedom
EE	End-Effector
ESC	Electronic Speed Controller
GPS	Global Positioning System
HC	Hierarchical Control
HGO	High Gain Observer
IMU	Inertial Measurement Unit
MoCap	Motion Capture System
SFL	Static Feedback Linearization
SLS	Standard Linear Solid
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Takeoff and Landing Vehicle

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