MPI Series in
Biological Cybernetics
No. 50, May 2017

MAX-PLANCK-GESELLSCHAFT

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Design, Modeling and Control of Aerial Robots for Physical Interaction and Manipulation

Design, Modeling and Control of Aerial Robots for Physical Interaction and Manipulation

Von der Fakultät Konstruktions-, Produktions- und Fahrzeugtechnik der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

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Tag der mündlichen Prüfung: 17. Februar 2017

Institut für Systemtheorie und Regelungstechnik

Universität Stuttgart

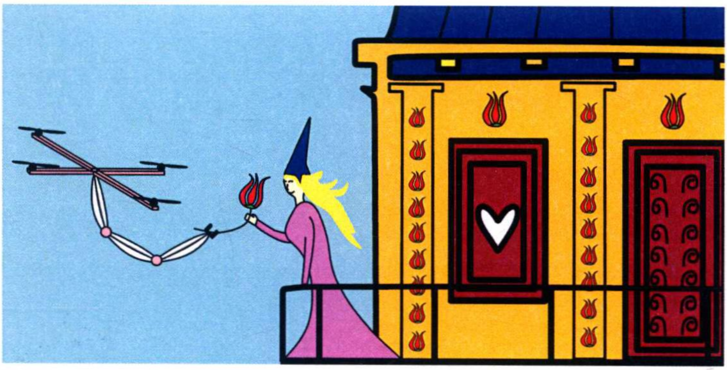
2017

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

ISBN 978-3-8325-4492-8

Logos Verlag Berlin GmbH
Comeniushof, Gubener Str. 47,
10243 Berlin
Tel.: +49 (0)30 42 85 10 90
Fax: +49 (0)30 42 85 10 92
INTERNET: http://www.logos-verlag.de



Acknowledgements

Essence of life. This is, like many of us, what I have been trying to identify in the course of my time until this very moment, in a train to Tübingen on planet Earth, that is in its own trajectory in our solar system, somewhere in the Milky Way in our universe, presumably in one of many.

During this time I got the impression that the life can have more than just one *ethos*, as long as it collects some meaning from them and becomes more cheerful while doing so. I believe the joy of wisdom is one of them, and the people to share this joy with is another. I was lucky to have these two in my life, especially during the time of my doctorate thesis work, which finally has forged this book/manuscript/thesis.

There have been so many people during this time with whom I have met, collaborated, shared great ideas and moments, and of course drinks in most of these occasions. I would like to start expressing my finest gratitudes to Dr. Antonio Franchi, who has been the major mentor not only of my PhD, but also my personal evolution from the day-one of my thesis work. Besides benefiting from his vast knowledge in the field of robotics and control engineering, I have learned a lot from him by observing his way of approaching different real life problems.

I would like to thank both Prof. Heinrich Bülthoff and Prof. Frank Allgöwer for their sincere support for my doctorate work. I owe the quality of this work to the facilities provided by Prof. Bülthoff and the Max Planck Society; and I would never have the chance to be able to finalize and defend this PhD thesis if I wouldn't have Prof. Allgöwer's supervision.

I like to express my sincere gratitudes to another great mentor, Prof. Cristian Secchi, because of his guidance on the nonlinear control theory and his friendship whenever it was needed. He is the person who walked me through the beauty of the energetic functions as a *lingua franca* for understanding different physical systems and their characteristics. He changed the way I see the world and our universe that we know of.

I would like to thank the Eiffel Excellence Scholarship for funding part of my PhD work in Toulouse, France, where I have got the chance to work with excellent scientists of CNRS-LAAS.

Furthermore, I was blessed with the most friendly and intelligent colleagues: Nicholas Staub, Marco Tognon, Gabriele Buondonno, Dr. Carlo Masone, Dr. Paolo Stegagno, Dr. Markus Ryll, Marcin Odelga, Sujit Rajappapa, Dr. Aamir Ahmad, Christian Schenk and everyone else in the labs of *Max Plank Institut für biologisches Kybernetik/Tübingen, CNRS-LAAS/Toulouse, DIAG-Sapienza Università/Roma.* Thank you all for the good moments we had and your competence in your fields.

My dearest friends; Stefano, Carlo, Mario, Nicole, Kresh, Christiane, Katha, Lotta, Frank, Merve, Eva, Aurelié, ... and all the others who have permanent places in my heart. Over the time you have become a great part of my life. Thank you for your (hopefully everlasting) friendship.

Finally, and above all, I would like to cherish here my family: my mother Ünzile, my father Halil and my sister Büşra. A beautiful set of people who are full of love and caring for all others. I consider myself very lucky for having them, their support and endless love in my life. I am also blessed with another family I have found in Germany; Evi, Frieder and Madita. You always make me feel home.

And of course, selbstverständlich, *Menja*. The light of my life. Who would I be without you? Thank you, millions of times, for always being on my side.

Regionalbahn from Stuttgart to Tübingen, May 2017
Burak Yüksel

Hep ilerleyeceğini umduğum insanlık için...

Yesterday I was clever and I wanted to change the world. Today I am wise, so I am changing myself. — Mevlana Celaleddin Rumi (1207 - 1273, Konya.)

Notation

Frames, Scalars, Vectors and Matrices

In this thesis, we used in general the following conventions;

- scalars are presented using normal weighted characters, e.g. $a \in \mathbb{R}$,
- vectors are denoted with boldfaced symbols, e.g. $\mathbf{v} \in \mathbb{R}^n$,
- matrices are indicated with capital boldfaced symbols, e.g. $\mathbf{M} \in \mathbb{R}^{n\times n}$.

For a vector $\mathbf{v} = [v_x \ v_y \ v_z]^T \in \mathbb{R}^3$, the operator $[\mathbf{v}]_\wedge : \mathbb{R}^3 \rightarrow \mathrm{so}(3)$ performs the skew-symmetric operation as

$$[\mathbf{v}]_\wedge = \begin{bmatrix} 0 & -v_z & v_y \\ v_z & 0 & -v_x \\ -v_y & v_x & 0 \end{bmatrix} \in \mathrm{so}(3).$$

The frames are shown with $\mathcal{F}_\star$, which are always described with the point placed at the center of the frame and three principle Cartesian axes. For example, the inertial (world) frame is denoted with $\mathcal{F}_W : \{\mathrm{P_W}, \mathbf{x}_W, \mathbf{y}_W, \mathbf{z}_W\}$. For the body frame of an aerial robot, it is $\mathcal{F}_B : \{\mathrm{P_B}, \mathbf{x}_B, \mathbf{y}_B, \mathbf{z}_B\}$.

The interconnection matrix, $\mathcal{J}$, and the dissipation matrix $\mathcal{R}$ in Chapter 4 are shown differently from the usual matrix convention used in the overall thesis.

Nomenclature

Here we list not all, but some important Greek/Latin characters used in this thesis.

$\mathbb{R}^n$	Set of real numbers in dimension of n
$\mathbb{N}$	Set of all natural numbers (in this thesis, including 0)
$\mathbb{Z}$	Set of all integers
$\mathbf{P}_\mathrm{B}, \mathbf{P}_{\mathrm{C}_0}$	Point placed at the Center of Mass (CoM) of the aerial robot
$\mathbf{P}_\mathrm{G}$	Point placed at the Center of Actuation (CoA) of the aerial robot
$\mathbf{x}_*, \mathbf{y}_*, \mathbf{z}_*$	Principal axes placed at point $\mathbf{P}_*$
$\mathbf{q}_q \in \mathbb{R}^6$	Generalized coordinates of $\mathbf{P}_\mathrm{B}$
$\mathbf{p}_q \in \mathbb{R}^3$	Position of $\mathbf{P}_\mathrm{B}$ in the world frame
$\mathbf{R} \in \mathbb{R}^{3\times3}$	Orientation of the body frame ($\mathcal{F}_B$) w.r.t. the world frame ($\mathcal{F}_W$)
$\boldsymbol{\eta} \in \mathbb{R}^3$	Minimal representation of $\mathbf{R}$ using *roll-pitch-yaw* convention
$\boldsymbol{\omega} \in \mathbb{R}^3$	Angular velocity of the aerial robot rigid body in $\mathcal{F}_B$
$\Omega_i \in \mathbb{R}$	Spinning velocity of the i-th propeller
$\mathbf{T} \in \mathbb{R}^{3\times3}$	Transformation matrix from $\dot{\boldsymbol{\eta}}$ to $\boldsymbol{\omega}$
$\mathbf{M}_{qr} \in \mathbb{R}^{3\times3}$	Quadrotor inertia matrix (of $\mathbf{P}_\mathrm{B}$ in $\mathcal{F}_B$)
$\mathbf{C}$	Coriolis matrix for a considered system dynamics
$\mathbf{g}$	Gravitational forces for a considered system dynamics
$\mathbf{G}$	Control input matrix for a considered system dynamics
$\mathbf{u}$	Control input vector for a considered system dynamics
$\mathbf{u}_r$	Torque vector acting to the CoM of the quadrotor
$\mathbf{d}$	Distance between two points
$\mathbf{w}_{ext}$	External wrench acting on the quadrotor CoM
u_t	Thrust intensity acting at the CoM of the aerial robot
ϕ, θ, ψ	Roll,Pitch,Yaw angles, respectively. Also, ϕ : elastic deflection in Sec. 6.2.8.
m_q	Mass of the aerial robot
k_e	Linear elastic spring constant
ω_n	Natural frequency
H	Total amount of energy (Hamiltonian) stored in a system
V	Lyapunov candidate
$\lVert * \rVert, \lVert * \rVert_2$	*2-norm* of $*$
$\lvert * \rvert$	Determinant of $*$

Abbreviations

APhI	Aerial Physical Interaction
BL	BrushLess
BL-CTRL	BrushLess-ConTROLler
CAD	Computer Aided Design
CAN	Controller Area Network
CoA	Center of Actuation
CoM	Center of Mass
DAQ	Data Acquisition Box
DFL	Dynamic Feedback Linearization
DoF	Degrees of Freedom
F/T	Force/Torque
IDA-PBC	Interconnection and Damping Assignment - Passivity Based Control
IMU	Inertial Measurement Unit
MAV	Micro Aerial Vehicle
MoCap	Motion Capture system
NED	North-East-Down
ODE	Ordinary Differential Equation
PC	Personal Computer
PDE	Partial Differential Equation
PH	Port Hamiltonian
PWM	Pulse Width Modulation
PVTOL	Planar Vertical Take-Off and Landing
ROS	Robot Operating System
UAV	Unmanned Aerial Vehicle
USB	Universal Serial Bus
UKF	Unscented Kalman Filter
VTOL	Vertical Take-Off and Landing

Abstract

Robots with flying capabilities, so called *aerial robots*, are essentially robotic platforms, which are autonomously controlled via some sophisticated control engineering tools. Similar to many *aerial vehicles* (e.g. fixed-wing planes or the helicopters which are already an important part of our lives since almost a century), they can overcome the gravitational forces thanks to their design and/or actuation type. What makes them different from the conventional aerial vehicles, is the level of their *autonomy*. Reducing the complexity for piloting of such robots/vehicles provide the human operator more freedom and comfort. Particularly the small size (or miniature) aerial robots (such as *quadrotors*) are becoming a bigger part of our lives, while they are rapidly advanced in the robotics society for improving our life quality. With their increasing autonomy, they can perform many complicated tasks by their own (such as surveillance, monitoring, or inspection), leaving the human operator the most high-level decisions to be made, if necessary. In this way they can be operated in hazardous and challenging environments, which might posses high risks to the human health. Thanks to their wide range of usage, the ongoing researches on these robots will have an increasing impact on the human life.

Over the past two decades, aerial robots have been extremely put in use for tasks e.g. surveillance, monitoring, filming, obstacle avoidance, etc. All these tasks had at least one thing in common: avoiding the flying robot any physical interaction with its environment. The obvious reason is because such interaction could lead the robot to a crash or to an unstable/uncontrolled scenario. This would be of course undesired, because it might finish the mission earlier than planned and even damage the fragile electronics onboard of the robot. In the time this thesis work had started, novel methods and technologies were becoming emerging needs on how to perform meaningful physical interaction tasks with aerial robots, while maintaining their stable flight.

Today, using the aerial robots for physical interaction and manipulation is a popular topic, with a great interest of many researchers. Including this thesis work, there have been various studies addressing the design, modeling and control problem of *Aerial Physical Interaction* (APhI) and *Aerial Manipulation*. A clear motivation of using aerial robots for physical interaction, is to benefit their great workspace and agility. Moreover, developing robots that can perform not only APhI but also aerial manipulation can bring the great workspace of the flying robots together with the vast dexterity of the manipulating arms. However achieving this is not only challenged by the limited technology, but also by the lack of sophisticated methods for handling the control of the system in a desired and stable way during physical interaction. It is important to note, that the APhI is still an open topic in many senses, and many studies are addressing it using different perspectives. This thesis work is one of those, which humbly tries to provide rigorous solutions to that problem using System/Control, Mechanics, Electronics and Computer Engineering tools.

In this doctoral thesis, the APhI and the *Aerial Manipulation* is studied in terms of *design*, *modeling* and *control* of aerial robots and manipulating arms; when they come together and become one system. Although fixed-wing planes, or helicopters can be (and

are) considered as aerial robots, during the course of this thesis we focus on the *quadrotors*, mostly because of their accessibility and *Vertical Take-off and Landing* (VTOL) ability. Using the *nonlinear* mathematical models of the robots at hand, here we propose several different control methods for APhI and aerial manipulation tasks. Furthermore, we present novel design tools (e.g. new manipulating arms) to be used together with miniature aerial robots, and contribute to the robotics society not only in terms of theory but also practical implementation and experimental robotics.

Deutsche Kurzfassung

Entwurf, Modellierung und Regelung eines fliegenden Roboters für physikalische Interaktion und Manipulation

Roboter mit Flugfähigkeit, sogenannte *fliegende Roboter*, sind Plattformen, die mittels Regelungsalgorithmen autonom gesteuert werden können. Analog zu zahllosen anderen *Fluggeräten* (z.B. die Starrflügelflugzeuge oder Hubschrauber) , können fliegende Roboter die Gravitationskraft, aufgrund ihres Designs und ihres Antriebs, überwinden. Was die fliegenden Roboter jedoch von konventionellen Flugzeugen unterscheidet, ist ihre *Autonomie.* Diese Autonomie macht die Steuerung solcher Roboter einfacher und komfortabler. Insbesondere kleine fliegende Roboter, wie die Quadrotoren, werden durch die stetige Weiterentwicklung ein immer wichtigerer Teil unseres täglichen Lebens. Durch ihre steigende Autonomie, können solche Roboter eine Vielzahl komplizierter Aufgaben, wie zum Beispiel die Überwachung und Inspektion, eigenständig ausführen. Da diese Roboter für eine Vielzahl von Aufgaben eingesetzt werden können, werden sie einen immer wichtigeren Einfluss auf unser Leben haben.

In den letzten 20 Jahren wurden fliegende Roboter für eine wachsende Anzahl von Aufgaben eingesetzt. Bei all diesen Aufgaben wurde jedoch eines immer vermieden: Die direkte physische Interaktion des fliegenden Roboters mit seiner Umgebung. Der offensichtliche Grund dafür ist, dass eine solche Interaktion dazu führen kann, dass der Roboter in einen instabilen Zustand gerät. Dies kann zum Absturz und damit zur Zerstörung der empfindlichen Elektronik des Roboters führen. Zu dem Zeitpunkt als die vorliegende Doktorarbeit ihren Anfang nahm, wurden deshalb dringend neue Methoden und Technologien benötigt, die eine sinnvolle physische Interaktion, bei stabilem Flug, ermöglichten. Heute ist die physische Interaktion von fliegenden Robotern ein beliebtes Thema, das von vielen Wissenschaftlern bearbeitet wird. Neben der vorliegenden Arbeit, wurden zahlreiche Studien durchgeführt, die das Design, die Modellierung und die Regelung der *Aerial Physical Interaction* (APhI) und der *Aerial Manipulation* zum Thema hatten. Der enorme Vorteil den fliegende Roboter bei der physischen Interaktion, gegenüber traditionellen Methoden haben, ist ihr große Reichweite und ihre Beweglichkeit. Wenn zudem Roboter entwickelt werden, die nicht nur mit der Umgebung interagieren können, sondern auch in der Lage sind, diese zu manipulieren, wird die große Reichweite der Roboter mit der enormen Geschicklichkeit der Manipulator-Arme ergänzt. Die Verbindung der Roboter mit einem solchen Manipulator-Arm ist jedoch aufgrund technischer Limitierungen und dem Fehlen ausgereifter Methoden, die eine stabiles Verhalten des Gesamtsystems während der Interaktion ermöglichen, eine

Herausforderung. Und auch heute noch sind viele Fragen, die die Interaktion von fliegenden Robotern mit ihrer Umgebung betreffen, ungeklärt und das Thema verschiedenster Studien. Die Arbeit, die in der vorliegenden Doktorarbeit beschrieben wird, ist ein Teil davon und versucht einen Beitrag zur Lösung dieser offenen Fragen beizutragen.

In der vorliegenden Doktorarbeit wird sowohl die *Aerial Physical Interaction* als auch die *Aerial Manipulation* in Bezug auf das Design, die Modellierung und die Regelung von fliegenden Robotern, Manipulator-Armen und dem Gesamtsystem aus beiden untersucht. Obwohl auch Starrflügelflugzeuge und Hubschrauber als fliegende Roboter betrachtet werden können und sollten, liegt der Fokus der vorliegenden Arbeit auf den *Quadrotoren*, unter anderem wegen ihrer Zugänglichkeit und weil diese in der Lage sind vertikal zu starten und zu landen. Mittels *nonlinearer* mathematischer Modelle dieser Roboter, werden in der vorliegenden Arbeit unterschiedliche Methoden zur Regelung und Steuerung der physischen Interaktion und Manipulation vorgeschlagen. Des Weiteren werden neue Werkzeuge (z.B. neue Manipulator-Arme) vorgestellt, die mit den fliegenden Robotern kombiniert werden können. Auf diese Weise kann die vorliegende Arbeit, neben theoretischen Methoden, auch mittels praktischer Anwendungen und Experimenten zum Fortschritt der Robotik beitragen.

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