$egin{aligned} \dot{oldsymbol{x}} &= f\left(oldsymbol{x},oldsymbol{u}
ight), \quad oldsymbol{x}\left(0
ight) = oldsymbol{x}_{0} \ oldsymbol{y} &= g\left(oldsymbol{x},oldsymbol{u}
ight) \end{aligned}$

 $egin{aligned} & \mathbf{\mathcal{X}}\left(s
ight) = \left(\mathbf{\mathcal{A}} - \mathbf{\mathcal{N}}
ight) \mathbf{\mathcal{X}}\left(s
ight) + \mathbf{\mathcal{N}} \ & \mathbf{\mathcal{N}}\left(s
ight) = \mathbf{\mathcal{CX}}\left(s
ight) + \mathbf{\mathcal{DU}}\left(s
ight) \end{aligned}$

 $oldsymbol{\Phi}\left(t,t_{0}
ight)=oldsymbol{A}\left(t
ight)oldsymbol{\Phi}\left(t,t_{0}
ight)$

Flight Control for Manned Multirotor Aircraft with Complex and Constrained Actuation Systems

Dipl.-Ing. Johannes Stephan

i<=N-1; i++)

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(xD[1+N+i] >= sat_1
(xD[1+2*N+i] >= sat_1
cD[1+2*N+i] >= sat

Universität Stuttgart Institut für Flugmechanik und Flugregelung

Fortschrittsberichte

Flight Control for Manned Multirotor Aircraft with Complex and Constrained Actuation Systems

A thesis accepted by the Faculty of Aerospace Engineering and Geodesy of the University of Stuttgart in partial fulfillment of the requirements for the degree of Doctor of Engineering Sciences (Dr.-Ing.)

by

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Date of defense:	November 4 th , 2019

Institute of Flight Mechanics and Controls University of Stuttgart

2020

Fortschrittsberichte des Instituts für Flugmechanik und Flugregelung

Band 10

Johannes Stephan

Flight Control for Manned Multirotor Aircraft with Complex and Constrained Actuation Systems

D 93 (Diss. Universität Stuttgart)

Shaker Verlag Düren 2020

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Stuttgart, Univ., Diss., 2019

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Printed in Germany.

ISBN 978-3-8440-7148-1 ISSN 2199-3483

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9 Internet: www.shaker.de • e-mail: info@shaker.de

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Nomenclature & Abbreviations

Symbols and abbreviations frequently used within this thesis are listed below in alphabetical order. Not included are symbols appearing only once or which are assumed to be clear from the context.

Greek Sy	mbols
Symbol	Descrip

Symbol	Description	Units
$\alpha \in [0,2\pi)$	Configuration angle	_
$\boldsymbol{\beta} = (\boldsymbol{\tau}_{\Sigma}^{\top} f_{\Sigma})^{\top}$	Pseudo control vector	Nm, N
$\delta \in [-1, 1]$	Pilot input	_
$\epsilon \in \{-1,1\}$	Propeller turning direction	_
$\eta \in (0, 1]$	Motor efficiency	_
$\mathbf{\Gamma} \in \mathbb{R}^{4 imes N}$	Control effectiveness matrix	
$\gamma > 0$	Bound on induced \mathscr{L}_2 -norm	
κ	Tilt angle	_
$\lambda \ge 0$	Propeller distance to CoG	m
$\hat{\omega} \ge 0$	Natural frequency	s^{-1}
$\Omega \geq 0$	Propeller angular velocity	s^{-1}
$\boldsymbol{\omega} = (p \ q \ r)^\top$	Body angular velocity	s^{-1}
$\mathbf{\Phi} = (\phi \; \theta \; \psi)^\top$	Euler angles	_
$\rho > 0$	Battery charge	\mathbf{C}
$\varrho_{ m tc}$	Tilt compensation gain	_
$\vartheta > 0$	Thrust-to-weight ratio	_
$\boldsymbol{ au}_{\Sigma} = (l \ m \ n)^{\top}$	Control torque	Nm
Υ	Linearized discharge dynamics	$A s^2$
ζ	Damping ratio	—

Roman Symbols

Symbol	Description	Units
$oldsymbol{A},oldsymbol{B},oldsymbol{C},oldsymbol{D}$	Linear state space matrices	
В	Number of batteries	_
\mathcal{B}	Index set over batteries	_
$c\in [0,1]$	Scaling factor	_
c_f, c_{τ}	Propeller thrust/drag coefficients	${ m Nms^2,Ns^2}$
$D_{\Gamma} \subset \mathbb{R}^4$	Control volume	Nm, N
$\boldsymbol{d}_{\tau}, d_f$	Disturbance torque/thrust	Nm, N
E_{Γ}	Control volume approximation	Nm, N
$E \ge 0$	Electric voltage	V
f_{Σ}	Thrust force	Ν
g	Gravitational acceleration	${ m ms^{-2}}$
h	Altitude	m
I_p, I_h	Error integral	s, m
$I \ge 0$	Electric current	А
$\boldsymbol{J}\succ 0$	Vehicle inertia	${\rm kg}{\rm m}^2$
$oldsymbol{K}_{(\cdot)}$	Feedback control gain	
$oldsymbol{L}_{(\cdot)}$	Anti-windup gain	
$\boldsymbol{M},\boldsymbol{X}$	LPV separation parameters	
m > 0	Vehicle mass	kg
N	Number of actuators	-
\mathcal{N}	Index set over actuators	-
N	Basis of nullspace $\ker(\Gamma)$	
0	Number of pseudo-controls, i.e., 4	-
$\boldsymbol{p} = (p_0 \ \boldsymbol{p}_v^\top)^\top$	Error quaternion	—
$\boldsymbol{P} \succ 0$	Lyapunov matrix	
$P \ge 0$	Electric power consumption	VA
$\boldsymbol{q} = (q_0 \ \boldsymbol{q}_v^\top)^\top$	Attitude quaternion	-
$R \ge 0$	Ohmic resistance	$\rm V A^{-1}$
S	Reference amplification	
$s\in \mathbb{C}$	Laplace variable	s^{-1}
t	Time	S
$U \subset \mathbb{R}^N$	Attainable control set	s^{-2}
$\boldsymbol{u}\in U$	Actuator commands	s^{-2}
$V \ge 0$	Lyapunov-candidate-function	
$\boldsymbol{W}\succ 0$	Allocation weights	

Symbol	Description
$(\cdot)_{\Delta}$	Acceleration command
$_{ m b}(\cdot)$	Body coordinate system
$(\cdot)_{ m cb}$	Battery charge balancing
$(\cdot)_{c}$	Reference or desired value
$\dot{(\cdot)}$	Time derivative $\frac{\partial(\cdot)}{\partial t}$
$(\cdot)_{\epsilon}$	Downdated/reduced variable
$(\cdot)_{\mathrm{e}}$	Error representation
$(\cdot)_{\mathrm{fb}}$	Feedback control
$(\cdot)_{\mathrm{ff}}$	Feed-forward control
$_{i}(\cdot)$	Inertial coordinate system
$\overline{(\cdot)}$	Upper limit
$\underline{(\cdot)}$	Lower limit
$(\cdot)^{\star}$	Optimal value
$(\cdot)_{\rm rot}$	Rotational domain
$_{r}(\cdot)$	Reference coordinate system
$(\cdot)^{\mathrm{T}}$	Transpose
$(\cdot)_0$	Trim control/command
$(\cdot)_{\mathrm{tc}}$	Tilt compensation
$(\cdot)_{\rm ver}$	Vertical translation

Subscripts, Superscripts, and Accents Symbol Description

Abbreviations

ACAH	Attitude command/attitude hold
ADS-33	Aeronautical Design Standard-33
AQ	Attitude quickness criteria
AW	Anti-windup
BIBO	Bounded-input, bounded-output
BRL	Bounded real lemma
BW	Bandwidth criteria
CGI	Cascaded Generalized Inverse
CoG	Center of gravity
DA	Damping criteria
ERP	Exact Redistributed Pseudoinverse
FCL	Flight control law
FCS	Flight control system
GNC	Guidance, navigation, & control
HQ	Handling quality

Nomenclature & Abbreviations

LiPo	Lithium-ion polymer battery
LMI	Linear matrix inequality
LPV	Linear parameter-varying
MaDoCo	Manned dodecacopter
MTE	Mission task element
MTOM	Maximum take-off mass
PAV	Personal aerial vehicle
RCDH	Rate command/direction hold
RT	Response type
SFAW	State-feedback anti-windup
SoC	State of charge
SP	System performance criteria
UCE	Usable cue environment
VRC	Vertical response characteristics
VTOL	Vertical take-off and landing

Notes:

The real and complex Euclidean spaces of dimension n and q are denoted \mathbb{R}^n and \mathbb{C}^q . Vector and matrix quantities are written in **bold**, where the former appear in lower case such as $\boldsymbol{v} \in \mathbb{R}^n$, and the latter are represented by capital characters as in $\boldsymbol{M} \in \mathbb{R}^{m \times n}$. If written element-wise, both vectors and matrices are enclosed by parentheses, i.e., $\boldsymbol{v} = (v_1 \ v_2)^{\mathrm{T}}$. The identity matrix of dimension $n \times n$ be \boldsymbol{I}_n and the $m \times n$ -matrix of zeros be $\boldsymbol{0}_{m,n}$.

Multiplication is commonly indicated by immediate juxtaposition, e.g., M v. However, in particular cases the multiplication sign \cdot is used as in $c \cdot v$ for improved clarity. Given the vectors $a, b \in \mathbb{R}^3$, the cross product is defined as $a \times b$.

Abstract

In the ongoing debate on future urban mobility, personal aerial vehicles are considered as a promising new mode of transportation. For a man-carrying multirotor, overall safety, reliability, and performance greatly depend on the fly-by-wire system. To this end, the design of suitable Guidance, Navigation, & Control algorithms is of pivotal importance to bring such concepts into commercial use.

This thesis presents a flight control framework for man-carrying multirotor flight. The proposed methods focus on specific challenges which distinguish these systems from typical unmanned aerial vehicles such as small quadcopter drones. The contributions can roughly be divided into three categories.

In the first part of this work, attention has been put on flight control design for multirotors with complex and severely constrained actuator configurations. Compared to small drones, the actuators of man-carrying systems are typically highly redundant. At the same time, the thrust-to-weight ratio of large aircraft tends to be relatively small. Against this background, the proposed controller involves novel schemes for allocation and anti-windup. The approach enables full exploitation of a complex actuator configuration. In addition, fast recovery from critical flight conditions is ensured via a state dependent prioritization strategy of attitude control. Overall, the framework guarantees stability of the rigid-body motion and good tracking performance for thrust-constrained manned multirotors, which is proven by virtue of rigorous stability analysis.

In the field of urban air mobility, facilitating the pilot's task is a key aspect to make the concept accessible to a wide group of users. The second part of this work thus focuses on the explicit implementation of desired handling qualities as part of the flight control design. The approach builds on renowned specifications for conventional rotorcraft. These are adjusted to the context of personal aerial vehicles and translated to requirements on the closed loop system dynamics, which can be applied as design criteria.

For the sake of safety and reliability, an electrically driven, manned multirotor must be equipped with a redundant energy supply system. The third part of this thesis evolves from the issue of non-uniform discharge between various battery units, which potentially leads to reduced endurance. As a counter measure, active charge balancing is presented. The approach is based on the idea to redistribute the energy consumption of the actuators to stabilize the drift. In this context, the charge balancing control action is restricted to input directions which are invariant with respect to the rigid-body motion. In this way, interference with the ordinary flight control task can be avoided.

The contributions of this thesis are supported by simulation data and successful flights on a two-seated multirotor aircraft with eighteen propellers and a take-off mass of approximately 450 kg. Using the proposed control laws, these tests led to a series of manned flights in spring 2019. The results underline the ability of the framework to address specific challenges of man-carrying multirotor flight control and therefore contribute to the realization of urban air mobility – a topic that must be approached given the potential impact on future transportation systems.

Kurzfassung

In der aktuellen Diskussion über zukünftige Mobilitätslösungen für Großstädte werden persönliche Luftfahrzeuge als vielversprechendes neues Verkehrsmittel genannt. Für einen bemannten Multikopter im urbanen Lufttransport trägt das Fly-by-Wire System maßgeblich zur Sicherheit, Zuverlässigkeit und Leistungsfähigkeit der Gesamtkonfiguration bei. Aus diesem Grund ist der Entwurf von geeigneten Algorithmen für die Navigation, Lenkung und Regelung von großer Bedeutung, um ein derartiges Konzept zu etablieren.

Diese Arbeit präsentiert einen modularen Ansatz zur Flugregelung für manntragende Multikopter. Der Schwerpunkt der vorgeschlagenen Methoden liegt auf spezifischen Herausforderungen, welche bei diesen Fahrzeugen im Vergleich zu kleinen Drohnen auftreten. Die Beiträge lassen sich dabei grob in drei Kategorien unterteilen.

Im ersten Teil liegt der Fokus auf dem Flugreglerentwurf für System mit komplexen und stark beschränkten Antriebskonfigurationen. Im Gegensatz zu kleinen Drohnen sind die Aktuatoren von bemannten Systemen in der Regel hochredundant. Gleichzeitig ist das Gesamtschub-zu-Gewichtsverhältnis größerer Multikopter für gewöhnlich vergleichsweise limitiert. Der vorgeschlagene Flugregler kombiniert neuartige Allokationsalgorithmen und Anti-Windup Methoden, wodurch die vollständige Nutzung einer komplexen Antriebskonfiguration ermöglicht wird. Um die schnelle Wiederherstellung des sicheren Flugs nach einer kritischen Auslenkung zu realisieren, verfügt das Regelgesetz über eine Strategie zur zustandsabhängigen Priorisierung der Lagestabilisierung. Aufgrund dieser Maßnahmen garantiert der Ansatz Stabilität und eine hohe Regelgüte für typisch ausgeprägte manntragende Multikopter, was mittels analytischen Stabilitätsuntersuchungen nachgewiesen wird.

Im Bereich der urbanen Luftmobilität ist das Vereinfachen der Pilotenaufgabe ein wichtiger Aspekt, um das Konzept einer großen Nutzergruppe zugänglich zu machen. Der zweite Teil der Arbeit konzentriert sich daher auf die explizite Implementierung von Handlingeigenschaften als Teil des Flugregelungsentwurfs. Der Ansatz basiert auf geläufigen Spezifikationen für konventionelle Hubschrauber. Diese werden dem Kontext von persönlichen Luftfahrzeugen angepasst und in Anforderungen an die Dynamik des geschlossenen Regelkreises übersetzt. Letztendlich ergeben sich so

quantitative Bedingungen, welche als Entwurfskriterien eingesetzt werden können.

Ein elektrisch angetriebener, bemannter Multikopter muss zwangsläufig ein redundantes Energieversorgungssystem aufweisen, um die benötigte Sicherheit und Verfügbarkeit zu garantieren. Der dritte Abschnitt dieser Arbeit widmet sich der Problematik von ungleichmäßiger Entladung zwischen verschiedenen Batterien, wodurch sich die Flugreichweite verringern kann. Als Gegenmaßnahme wird eine aktive Ladungsregelung vorgeschlagen. Hierbei wird der Verbrauch der Aktuatoren als Stellgröße genutzt um den Drift zu stabilisieren. Der Ansatz beschränkt sich auf Steuerrichtungen, welche bezüglich der Starrkörperbewegung invariant sind, um Wechselwirkungen mit der klassischen Flugregelung zu vermeiden.

Die Beiträge dieser Arbeit sind durch Simulationen und erfolgreiche Testflüge abgesichert. Als Versuchsträger kommt ein zweisitziger Multikopter mit achtzehn Propellern und einer Abflugmasse von 450 kg zum Einsatz. Im Frühjahr 2019 führte dies zu ersten bemannten Erprobungen des vorgeschlagenen Flugreglers. Diese Ergebnisse unterstreichen, dass das Konzept in der Lage ist, spezifische Herausforderungen in der Flugregelung bemannter Multikopter zu lösen. In diesem Sinne leistet die vorliegende Arbeit einen Beitrag zur Realisierung von urbaner Luftmobilität – ein Thema das aufgrund seiner Relevanz für die Transportsysteme der Zukunft adressiert werden muss.