WOODHEAD PUBLISHING
IN MECHANICAL ENGINEERING

Flight dynamics and system identification for modern feedback control

Avian-inspired robots

Jared A. Grauer and James E. Hubbard, Jr.

WP
WOODHEAD
PUBLISHING

Flight dynamics and system identification for modern feedback control

Avian-inspired robots

JARED A. GRAUER
AND
JAMES E. HUBBARD, JR.

WP
WOODHEAD
PUBLISHING

Oxford Cambridge Philadelphia New Delhi

Woodhead Publishing Limited, 80 High Street, Sawston, Cambridge, CB22 3HJ, UK
www.woodheadpublishing.com
www.woodheadpublishingonline.com

Woodhead Publishing, 1518 Walnut Street, Suite 1100, Philadelphia, PA 19102-3406, USA

Woodhead Publishing India Private Limited, G-2, Vardaan House, 7/28 Ansari Road,
Daryaganj, New Delhi – 110002, India
www.woodheadpublishingindia.com

First published in 2013, Woodhead Publishing Limited

© J. A. Grauer and J. E. Hubbard, Jr., 2013.

The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publisher cannot assume responsibility for the validity of all materials. Neither the authors not the publisher, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited for such copying.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2013931613

Woodhead Publishing ISBN: 978-0-85709-466-7 (print)

ISBN: 978-0-85709-467-4 (online)

Typeset by Domex e-Data Pvt. Ltd., India.

Printed in the UK and USA.

Flight dynamics and system identification for modern feedback control

For my family and friends

"There is a theory which states that if ever anybody discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states this has already happened."

-Douglas Adams

Nomenclature

Throughout this document, scalar mathematical symbols are represented by lower case characters, vectors by lower case bold characters, and matrices by upper case bold characters. Differentiation of a scalar quantity by a column vector results in a row vector.

Roman Symbols

$\mathbf{A}, \mathbf{B}$	linear system matrices
AR	aspect ratio
$\mathbf{a}(\mathbf{p}, \mathbf{v})$	generalized aerodynamic forces
a	acceleration vector
b	wing span
$\mathbf{C}(\mathbf{p}, \mathbf{v})$	dynamic coupling matrix
C_{ij}, K_{ij}	center of mass location and reference frame
C_x, C_y, C_z	force coefficient components
C_l, C_m, C_n	moment coefficient components
$\mathcal{C}$	controllability matrix
$\bar{c}$	mean aerodynamic chord
$\mathbf{e}_x$, $\mathbf{e}_y$, $\mathbf{e}_z$	elementary unit vectors
$\mathcal{F}\{.\}$	Fourier transform
f	frequency
f_f, $\mathcal{T}_f$	flapping frequency and period
$\mathbf{g}(\mathbf{p})$	generalized gravitational forces
g	acceleration vector due to gravity

$\mathbf{h}$	magnetic field vector
$\mathbf{I}$	inertia tensor
$\mathbb{I}$	identity matrix
$\Im\{.\}$, $\Re\{.\}$	imaginary and real parts
$\mathbf{J}_f$	force Jacobian matrix
$\mathbf{J}_\eta$	attitude Jacobian matrix
$J(\phi)$	cost function
j	imaginary number
L, M, N	body-fixed moment components
l, r	in-board and out-board position vectors
$\mathbf{M}(\mathbf{p})$	generalized mass matrix
m	scalar mass
n_p, n_v	number of position and velocity states
$\mathbf{p}$	generalized position vector
p, q, r	rotational body-fixed velocity components
Q	dynamic pressure
$\mathbf{R}$	rotation matrix
R^2	coefficient of determination
Re	Reynolds number
$\mathbf{r}$	position vector
S	reference area
$S(.)$	skew operator
$T(\mathbf{p}, \mathbf{v})$	kinetic energy
t	time
$U(\mathbf{p})$	potential energy
$\mathbf{u}$	perturbation control input vector
u, v, w	translational body-fixed velocity components
V	airspeed
$\mathbf{v}$	generalized velocity vector
$\mathbf{W}$	weighting matrix
X, Y, Z	body-fixed force components
$\mathbf{x}$	perturbation state vector
x, y, z	Cartesian position components
$\mathbf{y}$	model output vector
$\mathbf{Z}, z$	rotation axis matrix and vector
$\mathbf{z}$	physical state vector

Greek Symbols

α	angle of attack
β	sideslip angle
Γ	Hamel coefficient matrix
Δ	increment, perturbation
$\delta_w, \delta_{lon}, \delta_{lat}$	wing and tail control inputs
δ, ϵ	quaternion scalar and vector parts
η	orientation vector
θ	vector of articulated joint angles
λ, $\mathbf{v}$	Eigenvalue and Eigenvector
μ	physical control input vector
ν	translational velocity vector
ρ	density
Σ, σ^2	covariance matrix and scalar
τ	generalized force
$\Phi(t, t_0)$	state transition matrix
Φ, Ψ	kinematic Jacobian matrices
ϕ	parameter vector
ϕ, θ, ψ	roll, pitch, and yaw Euler angles
ω	angular velocity vector
ω	radian frequency

Superscripts

$^{-1}$	matrix inverse
^{T}	matrix transpose
$\dot{}$	time derivative
$\check{}$	ensemble average
*	trim value
$\hat{}$	estimated value

Subscripts

$_{ij}$	linkage *i* on kinematic chain *j*
$_m$	measured value

Other

$\lVert . \rVert_p$	p-norm
$\otimes$	Kronecker product

Acronyms

CAD	computer aided design
DC	direct current
EE	equation-error
IMU	inertial measurement unit
LTI	linear time-invariant
LTP	linear time-periodic
MEMS	micro electro-mechanical system
ODE	ordinary differential equation
OE	output-error
PSE	predicted square error
QUEST	quaternion estimator
SIDPAC	system identification programs for aircraft
TRIAD	tri-axial attitude determination system
UAV	unmanned air vehicle

Preface

"Ornithopters are mechanical contraptions that flap their wings like birds to generate aerodynamic forces... and they don't fly" was my uncharacteristically bold and naively undergraduate response to my (unbeknownst to me) future Ph.D. advisor's question as to whether anyone on my side of the video conference knew anything about ornithopters. He proceeded to tell me that in the time since da Vinci's drawings, ornithopters have been miniaturized and they do now, in fact, fly. Futhermore, he mentioned that he was aquiring a young flock of these birds and was eager to fly, and also that I was to be part of the research effort. And thus were sown the seeds for what took root and grew into an frustratingly enjoyable graduate school experience.

In addition to being a really cool project that liberated me from office walls on sunny days for flight testing, it turns out that ornithopters represent a good middle ground for designing small unmanned vehicles. As aircraft are made smaller, the air appears more viscous due to Reynolds effects, and so flapping wings and unsteady aerodynamics are needed to recover aerodynamic performance. However, the ability to carry sensor payloads diminish and sensitivity to gusts increase due to lower mass and inertia. A miniature ornithopter like that discussed in this monograph is well positioned to perform efficiently, carry payload, and fly in windy environments, as well as achieve agile and maneuverable flight, operate safely in close proximity to humans (despite buzzing videographers during flight tests), and don a degree of contextual camoflauge that has even fooled/attracted/scared other birds. Hence these ornithopters show great promise in aiding people in numerous aspects of life, from crop surveying to terrain mapping, and from military survellience to search and rescue missions.

The material presented herein has stemmed from my dissertation work, which occurred between 2005 and 2011. Needing periodic changes in scenery, I completed parts of this research were conducted at the University of Maryland, the National Institute of Aerospace, and the NASA Langley Research Center, but not in that order and not in one sitting. The original intent of the research was to develop wing morphing technologies using smart structures to actively change the wings in flight and to achieve agility on par with that of birds, or at least to land in a more controlled manner warranting an official label other than "munition." However, flight tests soon indicated that a stabilized flight platform was needed before an actively morphing wing could be implemented. However, flight tests soon indicated that new state estimation and control methods based on new flight dynamics models were needed before a stabilized flight platform could be achieved. Therefore, this book is devoted to developing a new model for ornithopter flight dynamics that is amenable to such tasks in dynamics as simulation, state estimation, system identification, and feedback control.

This book was written with clasped hands and slightly bent knees in the hopes of lifting others onto modest shoulders to see slightly further. The begining is fairly nontechnical: a description of the state of the art, some characterizations of the ornithopter platform, and the (difficult) differences between flapping-wing flight and conventional flight, all of which can be useful to a newcomer in the field or someone with a curious interest. However the pace soon quickens as nonlinear multibody dynamics are introduced and used to derive vehicle dynamics in a form useful for simulation, system identification, state estimation, and feedback control. As with any time the big picture comes finally into focus, I found the classical dynamics presented herin to be epiphanically clear, and I have tried to unify conventions from several references to present the material as I would have liked to learn it, in the hopes of reaching others in such related problems as multibody dynamics, rotor dynamics, aeroelasticity, and control of Euler-Lagrange systems. After the vehicle dynamics were derived, it remained to determine accurate and useful aerodynamic models. It is an understatement to say that this is difficult. Much of the literature has been devoted to analytic theory or conventional wind tunnel testing. Our approach was to combine our nonlinear multibody vehicle dynamics model, wind tunnel data, and flight test data with system identification methods to extract these methods. Completing that, the remainder of the manuscript examines the flight dynamics model, and investigates methods for trimming and linearizing the model, in order to complete that first goal of stabilizing the flight.

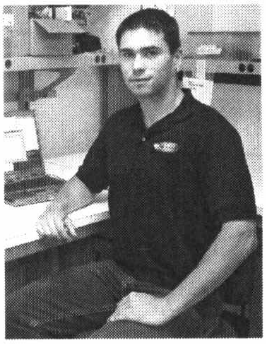
As with any journey that spans vast distances in both time and space, the list of those to whom I am thankfully indebted is unweildingly long. In this section I try to acknowledge those who have made the greatest impact on this work. Firstly is my family. My mother, Barbara Grauer, has fed the both the soul and the stomach their respective foods to endure. My father, Lawrence Grauer, in compliment has taught me the skills I have employeed to survive. My sisters Kathryn and Jennifer Grauer have given me a comfortable place to rest. My grandparents Judith Berry and Joyce Spittel have each given me outlets for my frustration. Aunts, uncles, cousins, and the like have all cheered me on. Secondly, the Morpheus Laboratory at the University of Maryland has been a warm center for creativity. Led by Dr. James Hubard, Jr., members of "Gen 1" (Nelson Guerreiro, Robyn Harmon, Benjamin Nickless, Geoff Slipher, and Sandra Ugrina) and "Gen 2" (Cornelia Altenbuchner, Alex Brown, and Aimy Wissa) have comprised what I can truly only describe as a wolf pack of a research group. Many thanks go to Dr. Sean Humbert for supplying equipement and discussions necessary for this work. Dr. Robert Sanner and Dr. Eugene Morelli additionally provided several long discussions that shaped the work. Wind tunnel tests were conducted with the help of Dr. Allan Winklemann, and flight tests were aided by Michael Chinn, Qina Diao, Imraan Faruque, Sarah Haack, Evan Ulrich, and Kan Yang.

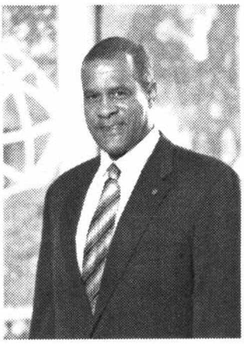
Jared Grauer
Hampton, Virginia
May 2012

About the authors

Dr. Grauer earned from the University of Maryland a bachelor's degree in 2005, a master's degree in 2007, and a Ph.D. in 2012. His graduate research experience included teaching, building miniature avionics packages, flying ornithopters, performing system identification on small unmanned air vehicles, and applying feedback control methods. He is currently a research aerospace engineer within the Dynamic Systems and Control Branch at the NASA Langley Research center, where he specializes in expanding system identification and feedback control techniques for new and exotic aircraft.

Dr. Hubbard began his career in 1971 as an engineering officer in the U.S. Merchant Marine serving in Vietnam. He received unlimited horsepower, steam and diesel engine Marine Engineering license from the U.S. Coast Guard and at the age of 19 was one of the youngest to get such an honor. He has served as a Professor of engineering at M.I.T., Boston University and is presently the Langley Distinguished Professor of Aerospace Engineering at the University of Maryland. His research involves the design, analysis, simulation and fabrication of spatially distributed systems, smart materials and smart transducers. He has co-founded three companies whose commercial product base built upon his experience in smart materials and smart sensors. He has received numerous awards for teaching and mentoring excellence including the M.I.T. Goodwin Medal for "Conspicuously Effective Teaching," The M.I.T. Stewart Award for "Outstanding Service to the Community," and in 2002 was awarded "The Key to the City" of his hometown, Danville Virginia for Lifetime achievement and mentoring. He is a Fellow of the AIAA and has more than 100 technical publications, 24 U.S. and Worldwide patents, and has served on numerous technical Boards and Committees of the National Academy of Engineering. He currently resides in Hampton Virginia with his 3 sons, James, Jordan, and Drew, and his wife Adrienne.





Contents