HANDBOOK OF MARINE CRAFT HYDRODYNAMICS AND MOTION CONTROL

Handbook of Marine Craft Hydrodynamics and Motion Control, First Edition. Thor I. Fossen.
 Published 2011 by John Wiley & Sons Ltd. ISBN: 978-1-119-99149-6

HANDBOOK OF MARINE CRAFT HYDRODYNAMICS AND MOTION CONTROL

Vademecum de Navium Motu Contra Aquas et de Motu Gubernando

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WILEY

A John Wiley & Sons, Ltd., Publication

This edition first published 2011

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

Library of Congress Cataloguing-in-Publication Data

Fossen, Thor I.
Handbook of Marine Craft Hydrodynamics and Motion Control / Thor Fossen.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-119-99149-6 (hardback)
1. Ships–Hydrodynamics. 2. Stability of ships. 3. Motion control devices.
4. Automatic pilot (Ships). 5. Steering-gear. 6. Ships–Electronic equipment. I. Title.
VM156.F67 2011
623.8'1–dc22

2010054228

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

Print ISBN: 9781119991496
E-PDF ISBN: 9781119994121
O-Book ISBN: 9781119994138
E-Pub ISBN: 9781119998686
Mobi ISBN: 9781119998693

Set in 9/11pt Times by Thomson Digital, Noida, India.

This book is dedicated to my parents Gerd Kristine and Ole Johan Fossen and my family Heidi, Sindre and Lone Moa who have always been there for me.

Thor I. Fossen

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About the Author

Professor Thor I. Fossen received an MSc degree in Marine Technology in 1987 from the Norwegian University of Science and Technology (NTNU) and a PhD in Engineering Cybernetics from NTNU in 1991. In the period 1989–1990 he pursued postgraduate studies in aerodynamics and flight control as a Fulbright Scholar at the University of Washington, Seattle. His expertise is in the fields of hydrodynamics, naval architecture, robotics, marine and flight control systems, guidance systems, navigation systems and nonlinear control theory. In 1993 he was appointed as a Professor of Guidance and Control at NTNU. He is one of the founders of the company Marine Cybernetics where he was the Vice President R&D in the period 2002-2007. He is the author of *Guidance and Control of Ocean Vehicles* (John Wiley & Sons, Ltd, 1994) and co-author of *New Directions in Nonlinear Observer Design* (Springer Verlag, 1999) and *Parametric Resonance in Dynamical Systems* (Springer Verlag, 2011). Professor Fossen has been instrumental in the development of several industrial autopilot, path-following and dynamic positioning (DP) systems. He has also experience in nonlinear state estimators for marine craft and automotive systems as well as strapdown GNSS/INS navigation systems. He has been involved in the design of the SeaLaunch trim and heel correction systems. He received the Automatica Prize Paper Award in 2002 for a concept for weather optimal positioning control of marine craft. He is currently head of automatic control at the Centre for Ships and Ocean Structures (CESOS), Norwegian Centre of Excellence, and a Professor of Guidance and Control in the Department of Engineering Cybernetics, NTNU.

Preface

The main motivation for writing this book was to collect new results on hydrodynamic modeling, guidance, navigation and control of marine craft that have been developed since I published my first book:

> Fossen, T. I. (1994). *Guidance and Control of Ocean Vehicles.* John Wiley & Sons, Ltd. Chichester, UK. ISBN 0-471-94113-1.

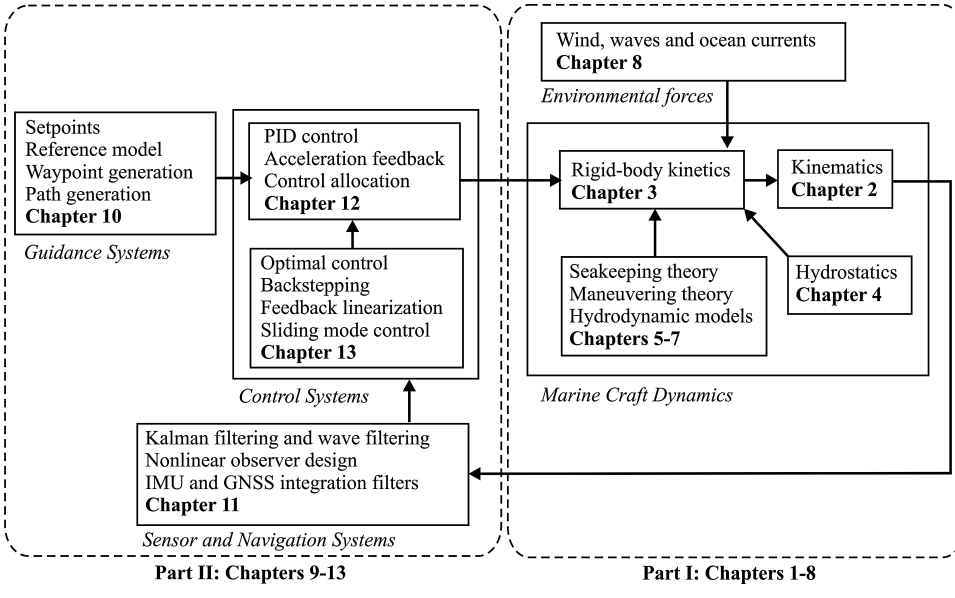
The Wiley book from 1994 was the first attempt to bring hydrodynamic modeling and control system design into a unified notation for modeling, simulation and control. My first book also contains state-of-the-art control design methods for ships and underwater vehicles up to 1994. In the period 1994–2002 a great deal of work was done on nonlinear control of marine craft. This work resulted in many useful results and lecture notes, which have been collected and published in a second book entitled *Marine Control Systems: Guidance, Navigation and Control of Ships and Underwater Vehicles*. The 1st edition was published in 2002 and it was used as the main textbook in my course on Guidance and Control at the Norwegian University of Science and Technology (NTNU). Instead of making a 2nd edition of the book, I decided to write the *Handbook of Marine Craft Hydrodynamics and Motion Control* and merge the most important results from my previous two books with recent results.

Part I of the book covers both maneuvering and seakeeping theory and it is explained in detail how the equations of motion can be derived for both cases using both frequency- and time-domain formulations. This includes transformations from the frequency to the time domain and the explanation of fluid-memory effects. A great effort has been made in the development of kinematic equations for effective representation of the equations of motion in seakeeping, body, inertial and geographical coordinates. This is very confusing in the existing literature on hydrodynamics and the need to explain this properly motivated me to find a unifying notation for marine and mechanical systems. This was done in the period 2002–2010 and it is inspired by the elegant formulation used in robotics where systems are represented in a vectorial notation. The new results on maneuvering and seakeeping are joint work with *Professor Tristan Perez*, University of Newcastle, Australia. The work with Professor Perez has resulted in several joint publications and I am grateful to him for numerous interesting discussions on hydrodynamic modeling and control. He should also be thanked for proofreading parts of the manuscript.

Part II of the book covers guidance systems, navigation systems, state estimators and control of marine craft. This second part of the book focuses on state-of-the-art methods for feedback control such as PID control design for linear and nonlinear systems as well as control allocation methods. A chapter with more advanced topics, such as optimal control theory, backstepping, feedback linearization and sliding-mode control, is included for the advanced reader. Case studies and applications are treated at the end of each chapter. The control systems based on PID and optimal control theory are designed with a complexity similar to those used in many industrial systems. The more advanced methods using nonlinear theory are included so the user can compare linear and nonlinear design techniques before a final implementation is

made. Many references to existing systems are included so control system vendors can easily find articles describing state-of-the art design methods for marine craft.

The arrangement of the subject matter in major parts can be seen from the following diagram:



Most of the results in the book have been developed at the Department of Engineering Cybernetics and the Centre of Ships and Ocean Structures, NTNU, in close cooperation with my former doctoral students, *Ola-Erik Fjellstad, Trygve Lauvdal, Jann Peter Strand, Jan Fredrik Hansen, Bjørnar Vik, Svein P. Berge, Mehrdad P. Fard, Karl-Petter Lindegaard, Ole Morten Aamo, Roger Skjetne, Ivar-Andre Flakstad Ihle, Andrew Ross, Gullik A. Jensen* and *Morten Breivik*, in the period 1991–2010. We have been a productive team, and have written hundreds of international publications in this period. Our joint efforts have resulted in several patents and industrial implementations. *Morten Breivik* has contributed with many important results on guidance systems (Chapter 10) and he should also be thanked for proofreading parts of the manuscript. *Bjarne Stenberg* should be thanked for creating the artistic front and back covers of the book and many other graphical illustrations. Finally, *Stewart Clark*, Senior Consultant, NTNU, should be thanked for his assistance with the English language. The book project has been sponsored by The Norwegian Research Council through the Center of Ships and Ocean Structures, Norwegian Center of Excellence at NTNU.

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