Guidance and Control of Ocean Vehicles

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This book is dedicated

to

Heidi and Sindre

Preface

My first interest for offshore technology and marine vehicles started during my "sivilingeniør" (MSc) study at the Department of Marine Systems Design at The Norwegian Institute of Technology (NIT). This interest was my main motivation for a doctoral study in Engineering Cybernetics at the Faculty of Electrical Engineering and Computer Sciences (NIT) and my graduate studies in flight control at the Department of Aeronautics and Astronautics, University of Washington, Seattle. Consequently, much of the material and inspiration for the book has evolved from this period. Writing this book, is an attempt to draw the disciplines of engineering cybernetics and marine engineering together.

Systems for Guidance and Control have been taught by the author since 1991 for MSc students in Engineering Cybernetics at the Faculty of Electrical Engineering and Computer Science (NIT). The book is intended as a textbook for senior and graduate students with some background in control engineering and calculus. Some basic knowledge of linear and nonlinear control theory, vector analysis and differential equations is required. The objective of the book is to present and apply advanced control theory to marine vehicles like remotely operated vehicles (ROVs), surface ships, high speed crafts and floating offshore structures. The reason for applying more sophisticated autopilots for steering and dynamic positioning of marine vehicles is mainly due to fuel economy, improved reliability and performance enhancement. Since 1973, the rapid increase in oil prices has contributed to this trend. This justifies the use of more advanced mathematical models and control theory in guidance and control applications.

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I want to express my gratitude to ABB Industry (Oslo), Robertson Tritech A/S (Egersund), the Norwegian Defence Research Establishment (Kjeller) and the Ulstein Group (Ulsteinvik) for contributing with full scale experimental results.

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The author is also grateful to his doctoral student Ola-Erik Fjellstad and Astrid Egeland for their useful comments and suggestions. Morten Brekke, Geir Edvin Hovland, Trygve Lauvdal and Kjetil Røe should be thanked for their help with illustrations, examples and computer simulations. The book also greatly benefits from students who took the course in guidance and control at NIT from 1991 to 1993. They have all helped me to reduce the number of typographical errors to an acceptable level. Finally, I want to thank Ms. Laura Denny and Mr. Stuart Gale (John Wiley & Sons Ltd.) who have provided me with technical and editorial comments to the final manuscript.

Thor I. Fossen
January 1994

Contents

Chapter 1

Introduction

The subject of this textbook is *guidance and control of ocean vehicles.* This title covers control systems design for all types of marine vehicles like submarines, torpedoes, unmanned and manned underwater vehicles, conventional ships, high speed crafts and semi-submersibles. Examples of such systems are:

- control systems for forward speed control
- autopilots for course-keeping and diving
- turning controllers
- track-keeping systems
- dynamic positioning (DP)
- rudder-roll stabilization (RRS)
- fin control systems
- wave-induced vibration damping

For practical purposes the discussion will concentrate on three vehicle categories: small unmanned underwater vehicles, surface ships and high speed craft.

Guidance and Control

The terms *guidance* and *control* can be defined so that:

GUIDANCE is the action of determining the course, attitude and speed of the vehicle, relative to some reference frame (usually the earth), to be followed by the vehicle.

CONTROL is the development and application to a vehicle of appropriate forces and moments for operating point control, tracking and stabilization. This involves designing the feedforward and feedback control laws.

The following example will be used to illustrate these definitions:

Example 1.1 (Automatic Weather Routing)
The design of an automatic weather routing system for a ship requires insight in both advanced modeling and optimal control theory. Moreover, we need an accurate model of the ship and the environmental forces (wind, waves and currents) to describe the speed loss of the ship in bad weather. Based on the speed loss computations we can compute a fuel optimal route. Finally, we have to design an optimal track-keeping controller (autopilot) to ensure that this route is followed by the ship.

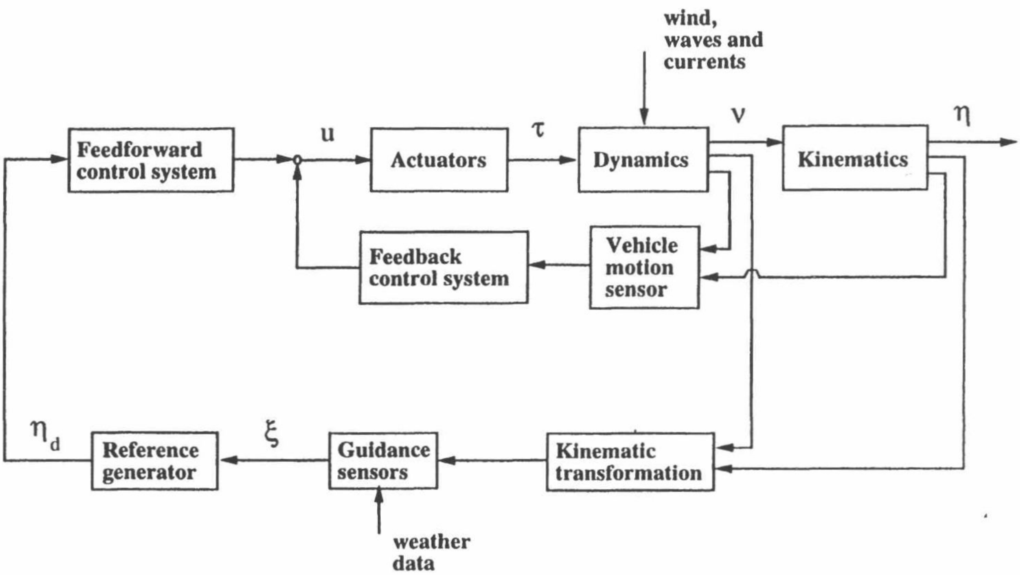

Figure 1.1: Guidance and control system for automatic weather routing of ships.

A guidance and control system for automatic weather routing of a ship is shown in Figure 1.1. This system uses weather data measurements to compute a fuel optimal route for the ship which is fed forward to the control system through a block denoted as the "feedforward control system". In addition to this, feedback is provided in an optimal manner from velocity $\boldsymbol{\nu}$ *and position/attitude* $\boldsymbol{\eta}$ *through the block "feedback control system". The control force and moment vector* $\boldsymbol{\tau}$ *is provided by the actuator via the control variable* $\boldsymbol{u}$*, which may be interpreted as the sum of the feedforward and feedback control action.*

We also notice that the reference generator $\boldsymbol{\eta}_d$ *may use weather data* $\boldsymbol{\xi}$ *(wind speed, wind direction, wave height etc.) together with the ship states* $(\boldsymbol{\nu}, \boldsymbol{\eta})$ *to compute the optimal route. This is usually done by including constraints for fuel consumption, actuator saturation, forward speed, restricted areas for ship maneuvering etc.*

□

An Overview of the Book

This book deals mainly with modeling and control of unmanned untethered underwater vehicles (remotely operated vehicles and autonomous underwater vehicles), surface ships (cargo ships, tankers etc.) and high speed craft (surface effect ships and foilborne catamarans).

The design of modern marine vehicle guidance and control systems requires knowledge of a broad field of disciplines. Some of these are vectorial kinematics and dynamics, hydrodynamics, navigation systems and control theory. To be able to design a high performance control system it is evident that a good mathematical model of the vehicle is required for simulation and verification of the design. As a result of this, the book contains a large number of mathematical models intended for this purpose. The different topics in the book are organized according to:

MODELING: marine vehicle kinematics and dynamics in 6 degrees of freedom (Chapter 2) and environmental disturbances in terms of wind, waves and currents (Chapter 3).

UNDERWATER VEHICLES: stability and control system design for small unmanned underwater vehicles (Chapter 4).

SURFACE SHIPS: ship dynamics, stability and maneuvering (Chapter 5) and ship control system design (Chapter 6).

HIGH SPEED CRAFT: control system design for surface effect ships (SES) and foilcats (Chapter 7).

It is recommended that one should read Chapter 2 before Chapters 3–7 since these chapters use basic results from vectorial kinematics and dynamics.

Chapter 2

Modeling of Marine Vehicles

Modeling of marine vehicles involves the study of *statics* and *dynamics*. Statics is concerned with the equilibrium of bodies at rest or moving with constant velocity, whereas dynamics is concerned with bodies having accelerated motion. Statics is the oldest of the engineering sciences. In fact, important contributions were made over 2000 years ago by Archimedes (287–212 BC) who derived the basic law of hydrostatic buoyancy. This result is the foundation for static stability analyses of marine vessels.

The study of dynamics started much later since accurate measurements of time are necessary to perform dynamic experiments. One of the first time-measuring instruments, a "water clock", was designed by Leonardo da Vinci (1452–1519). This simple instrument exploited the fact that the interval between the falling drops of water could be considered constant. The scientific basis of dynamics was provided by Newton's laws published in 1687. It is common to divide the study of dynamics into two parts: *kinematics*, which treats only geometrical aspects of motion, and *kinetics*, which is the analysis of the forces causing the motion.

Table 2.1: Notation used for marine vehicles.

DOF		forces and moments	linear and angular vel.	positions and Euler angles
1	motions in the x-direction (surge)	X	u	x
2	motions in the y-direction (sway)	Y	v	y
3	motions in the z-direction (heave)	Z	w	z
4	rotation about the x-axis (roll)	K	p	ϕ
5	rotation about the y-axis (pitch)	M	q	θ
6	rotation about the z-axis (yaw)	N	r	ψ

This study discusses the motion of marine vehicles in 6 *degrees of freedom* (DOF) since 6 independent coordinates are necessary to determine the position and orientation of a rigid body. The first three coordinates and their time derivatives correspond to the position and translational motion along the x-, y-, and