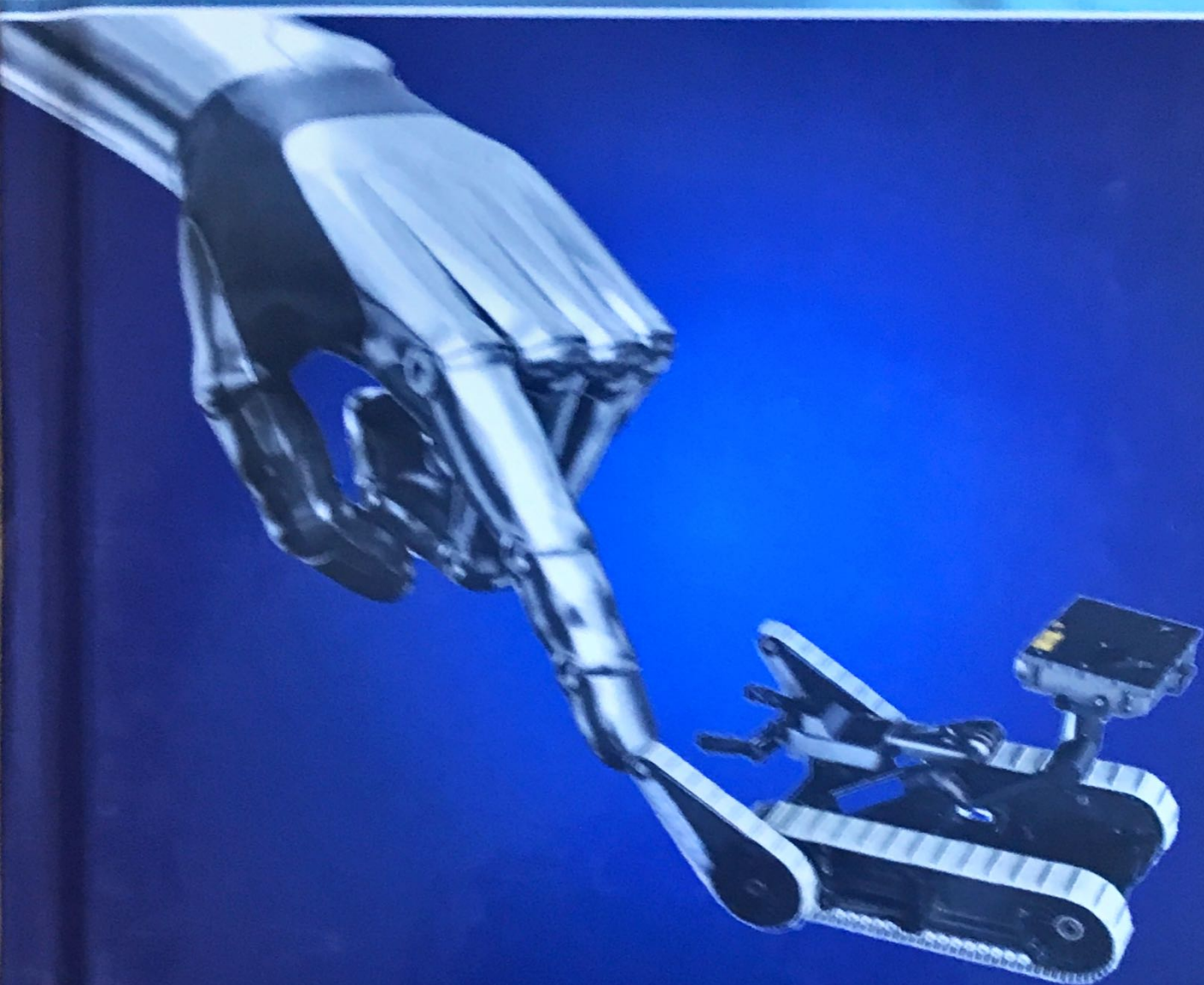




ELSEVIER INSIGHTS



INTRODUCTION TO MOBILE ROBOT CONTROL

SPYROS G. TZAFESTAS

Introduction to Mobile Robot Control

Introduction to Mobile Robot Control

Introduction to Mobile Robot Control

Spyros G. Tzafestas

*School of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece*



AMSTERDAM • BOSTON • HEIDELBERG • LONDON NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Elsevier

32 Jamestown Road, London NW1 7BY
225 Wyman Street, Waltham, MA 02451, USA

First edition 2014

Copyright © 2014 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangement with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein.

In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility. To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data

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

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-417049-0

For information on all Elsevier publications
visit our website at store.elsevier.com

This book has been manufactured using Print On Demand technology. Each copy is produced to order and is limited to black ink. The online version of this book will show color figures where appropriate.



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

Dedication

To the Robotics Teacher and Learner

For the things we have to learn before we can do them, we learn by doing them.

Aristotle

The second most important job in the world, second only to being a parent, is being a good teacher.

S.G. Ellis

In learning you will teach, and in teaching you will learn.

Phil Collins

Contents

Preface	xvii
List of acknowledged authors and collaborators	xix
Principal symbols and acronyms	xxiii
Quotations about robotics	xxv
1 Mobile Robots: General Concepts	1
1.1 Introduction	1
1.2 Definition and History of Robots	1
1.2.1 What Is a Robot?	1
1.2.2 Robot History	2
1.3 Ground Robot Locomotion	10
1.3.1 Legged Locomotion	10
1.3.2 Wheeled Locomotion	12
References	29
2 Mobile Robot Kinematics	31
2.1 Introduction	31
2.2 Background Concepts	31
2.2.1 Direct and Inverse Robot Kinematics	31
2.2.2 Homogeneous Transformations	35
2.2.3 Nonholonomic Constraints	38
2.3 Nonholonomic Mobile Robots	41
2.3.1 Unicycle	41
2.3.2 Differential Drive WMR	43
2.3.3 Tricycle	49
2.3.4 Car-Like WMR	50
2.3.5 Chain and Brockett—Integrator Models	55
2.3.6 Car-Pulling Trailer WMR	57
2.4 Omnidirectional WMR Kinematic Modeling	59
2.4.1 Universal Multiwheel Omnidirectional WMR	59
2.4.2 Four—Wheel Omnidirectional WMR with Mecanum Wheels	63
References	66

3 Mobile Robot Dynamics	69
3.1 Introduction	69
3.2 General Robot Dynamic Modeling	70
3.2.1 Newton–Euler Dynamic Model	71
3.2.2 Lagrange Dynamic Model	72
3.2.3 Lagrange Model of a Multilink Robot	73
3.2.4 Dynamic Modeling of Nonholonomic Robots	74
3.3 Differential-Drive WMR	74
3.3.1 Newton–Euler Dynamic Model	75
3.3.2 Lagrange Dynamic Model	78
3.3.3 Dynamics of WMR with Slip	82
3.4 Car-Like WMR Dynamic Model	86
3.5 Three-Wheel Omnidirectional Mobile Robot	92
3.6 Four Mecanum-Wheel Omnidirectional Robot	98
References	
 4 Mobile Robot Sensors	 101
4.1 Introduction	101
4.2 Sensor Classification and Characteristics	101
4.2.1 Sensor Classification	103
4.2.2 Sensor Characteristics	104
4.3 Position and Velocity Sensors	104
4.3.1 Position Sensors	105
4.3.2 Velocity Sensors	106
4.4 Distance Sensors	106
4.4.1 Sonar Sensors	108
4.4.2 Laser Sensors	109
4.4.3 Infrared Sensors	110
4.5 Robot Vision	110
4.5.1 General Issues	112
4.5.2 Sensing	117
4.5.3 Preprocessing	118
4.5.4 Image Segmentation	118
4.5.5 Image Description	119
4.5.6 Image Recognition	119
4.5.7 Image Interpretation	120
4.5.8 Omnidirectional Vision	

4.6	Some Other Robotic Sensors	126
4.6.1	Gyroscope	127
4.6.2	Compass	127
4.6.3	Force and Tactile Sensors	128
4.7	Global Positioning System	131
4.8	Appendix: Lens and Camera Optics	133
	References	134
5	Mobile Robot Control I: The Lyapunov-Based Method	137
5.1	Introduction	137
5.2	Background Concepts	137
5.2.1	State-Space Model	138
5.2.2	Lyapunov Stability	144
5.2.3	State Feedback Control	147
5.2.4	Second-Order Systems	149
5.3	General Robot Controllers	153
5.3.1	Proportional Plus Derivative Position Control	153
5.3.2	Lyapunov Stability-Based Control Design	155
5.3.3	Computed Torque Control	155
5.3.4	Robot Control in Cartesian Space	156
5.4	Control of Differential Drive Mobile Robot	159
5.4.1	Nonlinear Kinematic Tracking Control	159
5.4.2	Dynamic Tracking Control	163
5.5	Computed Torque Control of Differential Drive Mobile Robot	164
5.5.1	Kinematic Tracking Control	164
5.5.2	Dynamic Tracking Control	165
5.6	Car-Like Mobile Robot Control	169
5.6.1	Parking Control	170
5.6.2	Leader-Follower Control	172
5.7	Omnidirectional Mobile Robot Control	177
	References	182
6	Mobile Robot Control II: Affine Systems and Invariant Manifold Methods	185
6.1	Introduction	185
6.2	Background Concepts	186
6.2.1	Affine Dynamic Systems	186

6.2.2 Manifolds	193
6.2.3 Lyapunov Stability Using Invariant Sets	195
6.3 Feedback Linearization of Mobile Robots	199
6.3.1 General Issues	199
6.3.2 Differential-Drive Robot Input–Output Feedback Linearization and Trajectory Tracking	207
6.4 Mobile Robot Feedback Stabilizing Control Using Invariant Manifolds	220
6.4.1 Stabilizing Control of Unicycle in Chained Model Form	220
6.4.2 Dynamic Control of Differential-Drive Robots Modeled by the Double Brockett Integrator	222
6.4.3 Stabilizing Control of Car-Like Robot in Chained Model Form	225
References	234
7 Mobile Robot Control III: Adaptive and Robust Methods	237
7.1 Introduction	237
7.2 Background Concepts	238
7.2.1 Model Reference Adaptive Control	238
7.2.2 Robust Nonlinear Sliding Mode Control	240
7.2.3 Robust Control Using the Lyapunov Stabilization Method	244
7.3 Model Reference Adaptive Control of Mobile Robots	247
7.3.1 Differential Drive WMR	247
7.3.2 Adaptive Control Via Input–Output Linearization	249
7.3.3 Omnidirectional Robot	252
7.4 Sliding Mode Control of Mobile Robots	257
7.5 Sliding Mode Control in Polar Coordinates	259
7.5.1 Modeling	259
7.5.2 Sliding Mode Control	260
7.6 Robust Control of Differential Drive Robot Using the Lyapunov Method	263
7.6.1 Nominal Controller	265
7.6.2 Robustifying Controller	265
References	267
8 Mobile Robot Control IV: Fuzzy and Neural Methods	269
8.1 Introduction	269

8.2 Background Concepts	271
8.2.1 Fuzzy Systems	271
8.2.2 Neural Networks	275
8.3 Fuzzy and Neural Robot Control: General Issues	284
8.3.1 Fuzzy Robot Control	284
8.3.2 Neural Robot Control	288
8.4 Fuzzy Control of Mobile Robots	290
8.4.1 Adaptive Fuzzy Tracking Controller	290
8.4.2 Fuzzy Local Path Tracker for Dubins Car	296
8.4.3 Fuzzy Sliding Mode Control	301
8.5 Neural Control of Mobile Robots	310
8.5.1 Adaptive Tracking Controller Using MLP Network	310
8.5.2 Adaptive Tracking Controller Using RBF Network	314
8.5.3 Appendix: Proof of Neurocontroller Stability	315
References	316
9 Mobile Robot Control V: Vision-Based Methods	319
9.1 Introduction	319
9.2 Background Concepts	319
9.2.1 Classification of Visual Robot Control	319
9.2.2 Kinematic Transformations	320
9.2.3 Camera Visual Transformations	322
9.2.4 Image Jacobian Matrix	324
9.3 Position-Based Visual Control: General Issues	328
9.3.1 Point-to-Point Positioning	329
9.3.2 Pose-Based Motion Control	329
9.4 Image-Based Visual Control: General Issues	330
9.4.1 Use of the Inverse Jacobian	330
9.4.2 Use of the Transpose-Extended Jacobian	331
9.4.3 Estimation of the Image Jacobian Matrix	332
9.5 Mobile Robot Visual Control	335
9.5.1 Pose Stabilizing Control	335
9.5.2 Wall Following Control	338
9.5.3 Leader-Follower Control	339
9.6 Keeping a Landmark in the Field of View	342
9.7 Adaptive Linear Path Following Visual Control	349
9.7.1 Image Jacobian Matrix	349
9.7.2 The Visual Controller	351

9.8 Image-Based Mobile Robot Visual Servoing	357
9.9 Mobile Robot Visual Servoing Using Omnidirectional Vision	358
9.9.1 General Issues: Hyperbola, Parabola, and Ellipse equations	359
9.9.2 Catadioptric Projection Geometry	362
9.9.3 Omnidirectional Vision-Based Mobile Robot Visual Servoing	370
References	381
10 Mobile Manipulator Modeling and Control	385
10.1 Introduction	385
10.2 Background Concepts	385
10.2.1 The Denavit–Hartenberg Method	386
10.2.2 Robot Inverse Kinematics	388
10.2.3 Manipulability Measure	390
10.2.4 The Two-Link Planar Robot	391
10.3 MM Modeling	395
10.3.1 General Kinematic Model	395
10.3.2 General Dynamic Model	397
10.3.3 Modeling a Five Degrees of Freedom Nonholonomic MM	398
10.3.4 Modeling an Omnidirectional MM	403
10.4 Control of MMs	408
10.4.1 Computed-Torque Control of Differential-Drive MM	408
10.4.2 Sliding-Mode Control of Omnidirectional MM	409
10.5 Vision-Based Control of MMs	417
10.5.1 General Issues	417
10.5.2 Full-State MM Visual Control	421
References	427
11 Mobile Robot Path, Motion, and Task Planning	429
11.1 Introduction	429
11.2 General Concepts	430
11.3 Path Planning of Mobile Robots	432
11.3.1 Basic Operations of Robot Navigation	432
11.3.2 Classification of Path Planning Methods	433
11.4 Model-Based Robot Path Planning	434
11.4.1 Configuration Space	434

11.4.2	Road Map Path Planning Methods	435
11.4.3	Integration of Global and Local Path Planning	450
11.4.4	Complete Coverage Path Planning	454
11.5	Mobile Robot Motion Planning	457
11.5.1	General Online Method	457
11.5.2	Motion Planning Using Vector Fields	461
11.5.3	Analytic Motion Planning	463
11.6	Mobile Robot Task Planning	470
11.6.1	General Issues	470
11.6.2	Plan Representation and Generation	471
11.6.3	World Modeling, Task Specification, and Robot Program Synthesis	473
	References	476
12	Mobile Robot Localization and Mapping	479
12.1	Introduction	479
12.2	Background Concepts	480
12.2.1	Stochastic Processes	480
12.2.2	Stochastic Dynamic Models	482
12.2.3	Discrete-Time Kalman Filter and Predictor	483
12.2.4	Bayesian Learning	484
12.3	Sensor Imperfections	488
12.4	Relative Localization	489
12.5	Kinematic Analysis of Dead Reckoning	490
12.5.1	Differential Drive WMR	491
12.5.2	Ackerman Steering	492
12.5.3	Tricycle Drive	492
12.5.4	Omnidirection Drive	492
12.6	Absolute Localization	493
12.6.1	General Issues	493
12.6.2	Localization by Trilateration	493
12.6.3	Localization by Triangulation	496
12.6.4	Localization by Map Matching	497
12.7	Kalman Filter-Based Localization and Sensor Calibration and Fusion	499
12.7.1	Robot Localization	499
12.7.2	Sensor Calibration	501
12.7.3	Sensor Fusion	501

12.8 Simultaneous Localization and Mapping	505
12.8.1 General Issues	505
12.8.2 EKF SLAM	507
12.8.3 Bayesian Estimator SLAM	511
12.8.4 PF SLAM	515
12.8.5 Omnidirectional Vision-Based SLAM	517
References	530
13 Experimental Studies	533
13.1 Introduction	533
13.2 Model Reference Adaptive Control	533
13.3 Lyapunov-Based Robust Control	535
13.4 Pose Stabilizing/Parking Control by a Polar-Based Controller	536
13.5 Stabilization Using Invariant Manifold-Based Controllers	537
13.6 Sliding Mode Fuzzy Logic Control	540
13.7 Vision-Based Control	541
13.7.1 Leader-Follower Control	543
13.7.2 Coordinated Open/Closed-Loop Control	544
13.7.3 Omnidirectional Vision-Based Control	546
13.8 Sliding Mode Control of Omnidirectional Mobile Robot	551
13.9 Control of Differential Drive Mobile Manipulator	553
13.9.1 Computed Torque Control	553
13.9.2 Control with Maximum Manipulability	554
13.10 Integrated Global and Local Fuzzy Logic-Based Path Planner	557
13.10.1 Experimental Results	563
13.11 Hybrid Fuzzy Neural Path Planning in Uncertain Environments	564
13.11.1 The Path Planning Algorithm	565
13.11.2 Simulation Results	566
13.12 Extended Kalman Filter-Based Mobile Robot SLAM	567
13.13 Particle Filter-Based SLAM for the Cooperation of Two Robots	569
13.13.1 Phase 1 Prediction	569
13.13.2 Phase 2 Update	570
13.13.3 Phase 3 Resampling	571
13.13.4 Experimental Work	571

13.14	Neural Network Mobile Robot Control and Navigation	572
13.14.1	Trajectory Tracking	572
13.14.2	Navigation for Obstacle Avoidance	575
13.15	Fuzzy Tracking Control of Differential Drive Robot	578
13.16	Vision-Based Adaptive Robust Tracking Control of Differential Drive Robot	579
13.17	Mobile Manipulator Spherical Catadioptric Visual Control	582
	References	585
14	Generic Systemic and Software Architectures for Mobile Robot Intelligent Control	589
14.1	Introduction	589
14.2	Generic Intelligent Control Architectures	590
14.2.1	General Issues	590
14.2.2	Hierarchical Intelligent Control Architecture	590
14.2.3	Multiresolutional Intelligent Control Architecture	591
14.2.4	Reference Model Intelligent Control Architecture	593
14.2.5	Behavior-Based Intelligent Control Architectures	596
14.3	Design Characteristics of Mobile Robot Control Software Architectures	596
14.4	Brief Description of Two Mobile Robot Control Software Architectures	599
14.4.1	The Jde Component-Oriented Architecture	599
14.4.2	Layered Mobile Robot Control Software Architecture	601
14.5	Comparative Evaluation of Two Mobile Robot Control Software Architectures	603
14.5.1	Preliminary Issues	603
14.5.2	The Comparative Evaluation	605
14.6	Intelligent Human-Robot Interfaces	607
14.6.1	Structure of an Intelligent Human-Robot Interface	607
14.6.2	Principal Functions of Robotic HRIs	607
14.6.3	Natural Language Human-Robot Interfaces	609
14.6.4	Graphical Human-Robot Interfaces	610
14.7	Two Intelligent Mobile Robot Research Prototypes	612
14.7.1	The SENARIO Intelligent Wheelchair	613
14.7.2	The ROMAN Intelligent Service Mobile Manipulator	617
14.8	Discussion of Some Further Issues	621
14.8.1	Design for Heterogeneity	621
14.8.2	Modular Design	625
	References	629

15 Mobile Robots at Work	635
15.1 Introduction	635
15.2 Mobile Robots in the Factory and Industry	635
15.3 Mobile Robots in the Society	639
15.3.1 Mobile Manipulators for Rescue	639
15.3.2 Robotic Canes, Guiding Assistants, and Hospital Mobile Robots	640
15.3.3 Mobile Robots for Home Services	642
15.4 Assistive Mobile Robots	645
15.5 Mobile Telerobots and Web Robots	647
15.6 Other Mobile Robot Applications	652
15.6.1 War Robots	652
15.6.2 Entertainment Robots	656
15.6.3 Research Robots	659
15.7 Mobile Robot Safety	660
References	662
 Problems	 665
Robotics Web Sites	689