

Jorge Angeles

Fundamentals of Robotic Mechanical Systems

Theory, Methods, and Algorithms

Second Edition



Springer

Contents

Series Preface	vii
Preface to the Second Edition	ix
Preface to the First Edition	xi
1 An Overview of Robotic Mechanical Systems	1
1.1 Introduction	1
1.2 The General Structure of Robotic Mechanical Systems	3
1.3 Serial Manipulators.	6
1.4 Parallel Manipulators.	8
1.5 Robotic Hands.	11
1.6 Walking Machines.	13
1.7 Rolling Robots.	15
2 Mathematical Background	19
2.1 Preamble	19
2.2 Linear Transformations.	20
2.3 Rigid-Body Rotations.	25
2.3.1 The Cross-Product Matrix.	28
2.3.2 The Rotation Matrix	30
2.3.3 The Linear Invariants of a 3×3 Matrix.	34
2.3.4 The Linear Invariants of a Rotation.	35
2.3.5 Examples.	37

2.3.6	The Euler-Rodrigues Parameters	43
2.4	Composition of Reflections and Rotations	47
2.5	Coordinate Transformations and Homogeneous Coordinates	48
2.5.1	Coordinate Transformations Between Frames with a Common Origin	49
2.5.2	Coordinate Transformation with Origin Shift	52
2.5.3	Homogeneous Coordinates	54
2.6	Similarity Transformations	58
2.7	Invariance Concepts	63
2.7.1	Applications to Redundant Sensing	66
3	Fundamentals of Rigid-Body Mechanics	71
3.1	Introduction	71
3.2	General Rigid-Body Motion and Its Associated Screw	72
3.2.1	The Screw of a Rigid-Body Motion	74
3.2.2	The Pliicker Coordinates of a Line	76
3.2.3	The Pose of a Rigid Body	80
3.3	Rotation of a Rigid Body About a Fixed Point	83
3.4	General Instantaneous Motion of a Rigid Body	84
3.4.1	The Instant Screw of a Rigid-Body Motion	85
3.4.2	The Twist of a Rigid Body	88
3.5	Acceleration Analysis of Rigid-Body Motions	91
3.6	Rigid-Body Motion Referred to Moving Coordinate Axes	93
3.7	Static Analysis of Rigid Bodies	95
3.8	Dynamics of Rigid Bodies	99
4	Kinetostatics of Simple Robotic Manipulators	105
4.1	Introduction	105
4.2	The Denavit-Hartenberg Notation	106
4.3	The Kinematics of Six-Revolute Manipulators	113
4.4	The IKP of Decoupled Manipulators	117
4.4.1	The Positioning Problem	118
4.4.2	The Orientation Problem	133
4.5	Velocity Analysis of Serial Manipulators	138
4.5.1	Jacobian Evaluation	145
4.5.2	Singularity Analysis of Decoupled Manipulators	150
4.5.3	Manipulator Workspace	152
4.6	Acceleration Analysis of Serial Manipulators	156
4.7	Static Analysis of Serial Manipulators	160
4.8	Planar Manipulators	162
4.8.1	Displacement Analysis	163
4.8.2	Velocity Analysis	165
4.8.3	Acceleration Analysis	168
4.8.4	Static Analysis	170
4.9	Kinetostatic Performance Indices	171

4.9.1 Positioning Manipulators	176
4.9.2 Orienting Manipulators	179
4.9.3 Positioning and Orienting Manipulators	180
Trajectory Planning: Pick-and-Place Operations	189
5.1 Introduction	189
5.2 Background on PPO	190
5.3 Polynomial Interpolation	192
5.3.1 A 3-4-5 Interpolating Polynomial	192
5.3.2 A 4-5-6-7 Interpolating Polynomial	196
5.4 Cycloidal Motion	199
5.5 Trajectories with Via Poses	201
5.6 Synthesis of PPO Using Cubic Splines	202
Dynamics of Serial Robotic Manipulators	211
6.1 Introduction	211
6.2 Inverse vs. Forward Dynamics	211
6.3 Fundamentals of Multibody System Dynamics	213
6.3.1 On Nomenclature and Basic Definitions	213
6.3.2 The Euler-Lagrange Equations of Serial Manipulators	214
6.3.3 Kane's Equations	223
6.4 Recursive Inverse Dynamics	223
6.4.1 Kinematics Computations: Outward Recursions	224
6.4.2 Dynamics Computations: Inward Recursions	230
6.5 The Natural Orthogonal Complement in Robot Dynamics	234
6.5.1 Derivation of Constraint Equations and Twist-Shape Relations	240
6.5.2 Noninertial Base Link	244
6.6 Manipulator Forward Dynamics	244
6.6.1 Planar Manipulators	248
6.6.2 Algorithm Complexity	261
6.6.3 Simulation	265
6.7 Incorporation of Gravity Into the Dynamics Equations	268
6.8 The Modeling of Dissipative Forces	269
Special Topics in Rigid-Body Kinematics	273
7.1 Introduction	273
7.2 Computation of Angular Velocity from Point-Velocity Data	274
7.3 Computation of Angular Acceleration from Point-Acceleration Data	280
Kinematics of Complex Robotic Mechanical Systems	287
8.1 Introduction	287
8.2 The IKP of General Six-Revolute Manipulators	288

8.2.1	Preliminaries	289
8.2.2	The Bivariate-Equation Approach	302
8.2.3	The Univariate-Polynomial Approach	304
8.2.4	Numerical Conditioning of the Solutions	313
8.2.5	Computation of the Remaining Joint Angles	314
8.2.6	Examples	317
8.3	Kinematics of Parallel Manipulators	322
8.3.1	Velocity and Acceleration Analyses of Parallel Manipulators	337
8.4	Multifingered Hands	343
8.5	Walking Machines	348
8.6	Rolling Robots	352
8.6.1	Robots with Conventional Wheels	352
8.6.2	Robots with Omnidirectional Wheels	358
9	Trajectory Planning: Continuous-Path Operations	363
9.1	Introduction	363
9.2	Curve Geometry	364
9.3	Parametric Path Representation	370
9.4	Parametric Splines in Trajectory Planning	383
9.5	Continuous-Path Tracking	389
10	Dynamics of Complex Robotic Mechanical Systems	401
10.1	Introduction	401
10.2	Classification of Robotic Mechanical Systems with Regard to Dynamics	402
10.3	The Structure of the Dynamics Models of Holonomic Systems	403
10.4	Dynamics of Parallel Manipulators	406
10.5	Dynamics of Rolling Robots	417
10.5.1	Robots with Conventional Wheels	417
10.5.2	Robots with Omnidirectional Wheels	427
A	Kinematics of Rotations: A Summary	437
B	The Numerical Solution of Linear Algebraic Systems	445
B.I	The Overdetermined Case	446
B.I.I	The Numerical Solution of an Overdetermined System of Linear Equations	447
B.2	The Underdetermined Case	451
B.2.1	The Numerical Solution of an Underdetermined System of Linear Equations	452
Exercises		455
1	An Overview of Robotic Mechanical Systems	455
2	Mathematical Background	457

3	Fundamentals of Rigid-Body Mechanics	465
4	Kinetostatics of Simple Robotic Manipulators	471
5	Trajectory Planning: Pick-and-Place Operations	478
6	Dynamics of Serial Robotic Manipulators	481
7	Special Topics on Rigid-Body Kinematics	487
8	Kinematics of Complex Robotic Mechanical Systems	490
9	Trajectory Planning: Continuous-Path Operations	494
10	Dynamics of Complex Robotic Mechanical Systems.	498

References	501
-------------------	------------

Index	515
--------------	------------