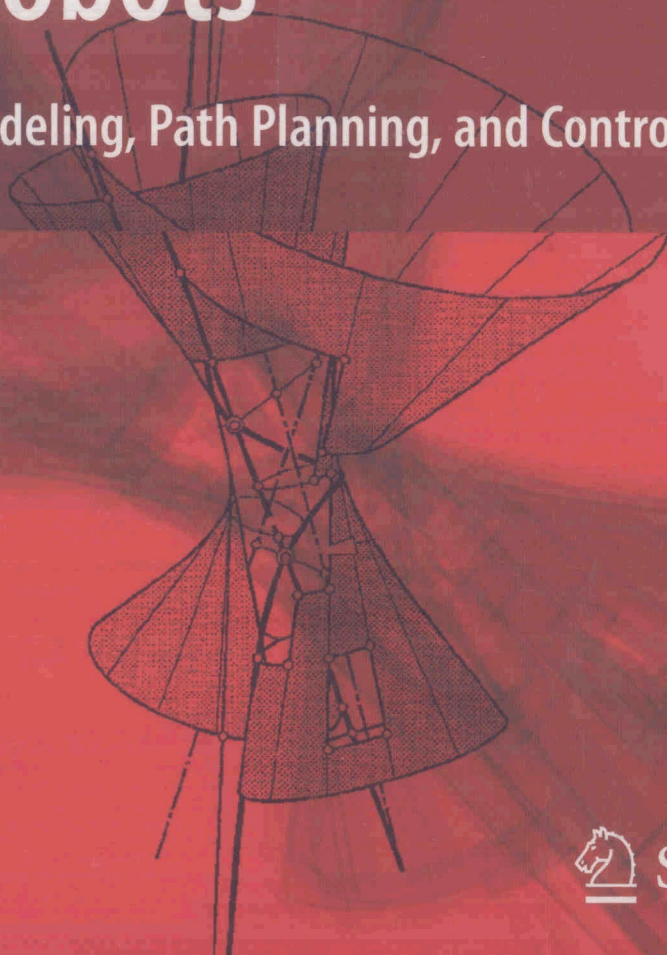


Farbod Fahimi

Autonomous Robots

Modeling, Path Planning, and Control



Springer

Contents

1	Introduction	1
1.1	Redundant Manipulators	1
1.1.1	Kinematics	1
1.1.2	Redundancy Resolution	1
1.1.3	Use for Redundancy	2
1.1.4	Mathematical Solution Methods	3
1.2	Hyper-Redundant Manipulators	3
1.3	Mobile Robots	5
1.3.1	Common Types	5
1.3.2	Applications of Mobile Robots	7
1.4	Autonomous Surface Vessels	8
1.4.1	Military and Security Applications	8
1.4.2	Civilian Applications	9
1.5	Autonomous Helicopters	10
1.5.1	Research Platforms	10
1.5.2	Civilian Applications	12
1.5.3	Security and Military Applications	12
1.5.4	Mathematical Models and Methods	13
1.6	Summary	13
2	Redundant Manipulators	15
2.1	Introduction	15
2.1.1	Kinematics of Redundant Manipulators	16
2.2	Redundancy Resolution at the Velocity Level	20
2.2.1	Exact Solutions	20
2.2.2	Approximate Solution Methods	26
2.3	Redundancy Resolution at the Position Level	30
2.4	Joint Limit Avoidance and Obstacle Avoidance	34
2.4.1	Joint Limit Avoidance (JLA)	34
2.4.2	Obstacle Avoidance	42
2.5	Summary	48
	Problems	48

3	Hyper-Redundant Manipulators	51
3.1	Introduction	51
3.2	Parameterization of the Backbone Curve	52
3.2.1	Workspace Considerations	56
3.3	Fitting Methods	57
3.3.1	Constraint Least Square Fitting Method (CLSFM)	57
3.3.2	Recursive Fitting Method (RFM)	63
3.3.3	Comparison Between the CLSFM and the RFM	69
3.4	Inverse Velocity Propagation	70
3.4.1	Velocity of a Point on the Backbone Curve	70
3.4.2	Linear Velocity of Joints Located on the Backbone Curve	74
3.4.3	Joint Angular Velocities	76
3.4.4	Singularity Considerations in Inverse Velocity Propagation	77
3.5	Summary	78
	Problems	78
4	Obstacle Avoidance Using Harmonic Potential Functions	81
4.1	Introduction	81
4.2	Potential Theory and Harmonic Functions	83
4.2.1	Properties of Harmonic functions	83
4.3	Two-Dimensional Harmonic Potential Functions	84
4.3.1	Potential of a Point Source or a Point Sink	85
4.3.2	Potential of a Uniform Flow	86
4.3.3	Potential of a Line Segment (a Panel)	88
4.3.4	Superposition of Potentials	90
4.3.5	Multiple Line Obstacles	93
4.3.6	Uniform Flow	98
4.3.7	Goal Sink	98
4.4	Two-Dimensional Robust Harmonic Potential Field	102
4.5	Path Planning for a Single Mobile Robot	105
4.5.1	Algorithm for a Single Robot	105
4.6	Path Planning for Multiple Mobile Robots	106
4.6.1	Algorithm for Multiple Robots	108
4.7	Structural Local Minimum and Stagnation Points	111
4.8	Three-Dimensional Harmonic Potential Functions	111
4.8.1	Uniform Flow	111
4.8.2	Goal Sink	112
4.8.3	Spatial Panel	114
4.9	Three-Dimensional Robust Harmonic Potential Field	119
4.10	Path Planning for Aerial Robots or Hyper-Redundant Manipulators	123
4.10.1	Algorithm for an Aerial Robot	123

4.11	Summary	126
	Problems	127
5	Control of Manipulators	131
5.1	Introduction	131
5.2	Evolving Control Requirements	131
5.3	General Dynamic Model	132
5.3.1	Standard Second-Order Form	132
5.3.2	Standard First-Order Form	134
5.4	Position Control	135
5.5	Trajectory-Tracking Control	139
5.5.1	Feedback Linearization	140
5.5.2	Robust Control	146
	Problems	159
6	Mobile Robots	163
6.1	Introduction	163
6.2	Kinematic Models of Mobile Robots	163
6.2.1	Hilare Mobile Robots	163
6.2.2	Car-Like Mobile Robots	166
6.3	Trajectory-Tracking Control Based on Kinematic Models	168
6.3.1	Hilare-Type Mobile Robots	168
6.3.2	Car-Like Mobile Robots	175
6.4	Formation Control for Hilare Mobile Robots	182
6.4.1	Geometrical Leader-Follower Formation Schemes	183
6.4.2	Design of the $l - \alpha$ Controller	183
6.4.3	Design of the $l - l$ Controller	188
6.5	Dynamics of Mobile Robots	194
6.5.1	Hilare-Type Mobile Robots	194
6.6	Trajectory-Tracking Control Based on Dynamic Models	201
6.6.1	Hilare-Type Mobile Robots	202
	Problems	217
7	Autonomous Surface Vessels	221
7.1	Introduction	221
7.2	Dynamics of a Surface Vessel	222
7.3	The Control Point Concept for Underactuated Vehicles	225
7.3.1	The Role of the Control Point	225
7.4	Zero-Dynamics Stability for a Surface Vessel	226
7.4.1	Stability in Case of General Motions with Constant Speed	228
7.4.2	Equilibrium Point for Circular and Linear Motions with Constant Speed	229
7.4.3	Permissible Practical Motions	230

7.5	Trajectory-Tracking Controller Design	230
7.5.1	The Input–Output Relations	231
7.5.2	Feedback Linearization	232
7.5.3	Robust Control Using the Sliding Mode Method	237
7.6	Formation Control for Surface Vessels	244
7.6.1	Geometrical Leader-Follower Formation Schemes	244
7.6.2	Design of the $l - \alpha$ Controller	245
7.6.3	Design of the $l - l$ Controller	252
7.6.4	Implementation Notes	256
7.7	Summary	260
	Problems	260
8	Autonomous Helicopters	263
8.1	Introduction	263
8.2	A 6-DOF Dynamic Model of a Helicopter	264
8.3	Position Control for Autonomous Helicopters	267
8.3.1	The Hover Trimming Angles	268
8.3.2	The Longitudinal and Lateral Control Law	270
8.3.3	The Latitude and Altitude Control Law	271
8.4	The Control Point Concept for Underactuated Vehicles	275
8.4.1	The Role of the Control Point	276
8.5	Robust Trajectory-Tracking Control for Autonomous Helicopters	277
8.5.1	The Input–Output Equations	278
8.5.2	Robust Control Using the Sliding Mode Method	280
8.6	Leader-Follower Formation Control for Autonomous Helicopters	287
8.6.1	Formation Control Schemes	289
8.6.2	Designing the Sliding Mode Control Law	300
	Problems	312
A	Mathematics	319
A.1	Null Space	319
A.2	Rank	320
A.3	Singular Value Decomposition (SVD)	320
A.3.1	Computing SVD	321
A.4	Pseudo-Inverse for a Rectangular Matrix	323
A.5	Bisection Method	323
B	Control Methods Review	325
B.1	Feedback Linearization	325
B.2	Sliding Mode Control	326
	References	331
	Index	337