
Contents

List of Figures	xxiii
-----------------------	-------

Part I Preliminaries

Introduction to Part I	3
1 What Does “Control of Robots” Involve?	7
1.1 Familiarization with the Physical System under Consideration .	8
1.2 Dynamic Model	10
1.3 Control Specifications	12
1.4 Motion Control of Robot Manipulators	12
Bibliography	15
2 Mathematical Preliminaries	19
2.1 Linear Algebra	20
2.2 Fixed Points	26
2.3 Lyapunov Stability	27
2.3.1 The Concept of Equilibrium	28
2.3.2 Definitions of Stability	31
2.3.3 Lyapunov Functions	40
2.3.4 Lyapunov’s Direct Method	44
Bibliography	53
Problems	54
3 Robot Dynamics	59

3.1	Lagrange's Equations of Motion	62
3.2	Dynamic Model in Compact Form	71
3.3	Dynamic Model of Robots with Friction	75
3.4	Dynamic Model of Elastic-joint Robots	77
3.5	Dynamic Model of Robots with Actuators	82
	Bibliography	88
	Problems	90
4	Properties of the Dynamic Model	95
4.1	The Inertia Matrix	95
4.2	The Centrifugal and Coriolis Forces Matrix	97
4.3	The Gravitational Torques Vector	101
4.4	The Residual Dynamics	102
4.5	Conclusions	108
	Bibliography	109
	Problems	110
5	Case Study: The Pelican Prototype Robot	113
5.1	Direct Kinematics	115
5.2	Inverse Kinematics	116
5.3	Dynamic Model	119
5.3.1	Lagrangian Equations	119
5.3.2	Model in Compact Form	123
5.4	Desired Reference Trajectories	128
	Bibliography	131
	Problems	131

Part II Position Control

Introduction to Part II	135
Bibliography	139
6 Proportional Control plus Velocity Feedback and PD Control	141
6.1 Robots without Gravity Term	143
6.2 Robots with Gravity Term	146
6.2.1 Unicity of the Equilibrium	146

6.2.2	Arbitrarily Bounded Position and Velocity Error	148
6.3	Conclusions	153
	Bibliography	153
	Problems	153
7	PD Control with Gravity Compensation	157
7.1	Global Asymptotic Stability by La Salle's Theorem	159
7.2	Lyapunov Function for Global Asymptotic Stability	163
7.2.1	Positivity of the Lyapunov Function	164
7.2.2	Time Derivative of the Lyapunov Function	165
7.3	Conclusions	167
	Bibliography	167
	Problems	168
8	PD Control with Desired Gravity Compensation	171
8.1	Boundedness of Position and Velocity Errors, \bar{q} and \dot{q}	174
8.2	Unicity of Equilibrium	180
8.3	Global Asymptotic Stability	181
8.4	Lyapunov Function for Global Asymptotic Stability	190
8.5	Conclusions	195
	Bibliography	195
	Problems	196
9	PID Control	201
9.1	Lyapunov Function Candidate	207
9.2	Time Derivative of the Lyapunov Function Candidate	209
9.3	Asymptotic Stability	211
9.4	Tuning Procedure	213
9.5	Conclusions	216
	Bibliography	217
	Problems	218

Part III Motion Control

Introduction to Part III	223
10 Computed-torque Control and Computed-torque+ Control	227

10.1	Computed-torque Control	227
10.2	Computed-torque+ Control	232
10.3	Conclusions	237
	Bibliography	238
	Problems	239
11	PD+ Control and PD Control with Compensation	243
11.1	PD Control with Compensation	244
11.2	PD+ Control	248
11.2.1	Lyapunov Function for Asymptotic Stability	253
11.3	Conclusions	258
	Bibliography	259
	Problems	260
12	Feedforward Control and PD Control plus Feedforward	263
12.1	Feedforward Control	264
12.2	PD Control plus Feedforward	269
12.2.1	Unicity of the Equilibrium	271
12.2.2	Global Uniform Asymptotic Stability	273
12.3	Conclusions	282
	Bibliography	282
	Problems	284
<hr/>		
Part IV Advanced Topics		
<hr/>		
	Introduction to Part IV	289
13	P“D” Control with Gravity Compensation and P“D” Control with Desired Gravity Compensation	291
13.1	P“D” Control with Gravity Compensation	292
13.2	P“D” Control with Desired Gravity Compensation	300
13.3	Conclusions	307
	Bibliography	308
	Problems	309
14	Introduction to Adaptive Robot Control	313
14.1	Parameterization of the Dynamic Model	314

14.1.1	Linearity in the Dynamic Parameters	315
14.1.2	The Nominal Model	319
14.2	The Adaptive Robot Control Problem.....	325
14.3	Parameterization of the Adaptive Controller	327
14.3.1	Stability and Convergence of Adaptive Control Systems	329
	Bibliography	331
	Problems	334
15	PD Control with Adaptive Desired Gravity Compensation.	337
15.1	The Control and Adaptive Laws	338
15.2	Stability Analysis.....	342
15.3	Examples	349
15.4	Conclusions	357
	Bibliography	358
	Problems	359
16	PD Control with Adaptive Compensation	361
16.1	The Control and Adaptive Laws	361
16.2	Stability Analysis.....	365
16.3	Examples	368
16.4	Conclusions	377
	Bibliography	377
	Problems	378

Appendices

A	Mathematical Support	383
A.1	Some Lemmas on Linear Algebra	383
A.2	Vector Calculus	384
A.3	Functional Spaces	390
	Bibliography	397
	Problems	398
B	Support to Lyapunov Theory	401
B.1	Conditions for Positive Definiteness of Functions	401
C	Proofs of Some Properties of the Dynamic Model	407

D Dynamics of Direct-current Motors	411
D.1 Motor Model with Linear Friction	416
D.2 Motor Model with Nonlinear Friction	417
Bibliography	418
Index	419