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
Contents

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
Contents xix

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, \( \ddot{q} \) 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
### Contents

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

---

**Part IV Advanced Topics**

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
Control of Robot Manipulators in Joint Space
Kelly, R.; Santibáñez Davila, V.; Loría Perez, J.A.
2005, XXVI, 426 p. 110 illus. With online files/update.,
Softcover
ISBN: 978-1-85233-994-4