Contents

List of Figures  xiii
List of Tables  xxv
Preface  xxvii
Acknowledgments  xxxiii
Acronyms  xxxv

Part I  Pseudoinverse-Based ZD Approach  1

1  Redundancy Resolution via Pseudoinverse and ZD Models  3
1.1 Introduction  3
1.2 Problem Formulation and ZD Models  5
1.2.1 Problem Formulation  5
1.2.2 Continuous-Time ZD Model  6
1.2.3 Discrete-Time ZD Models  7
1.2.3.1 Euler-Type DTZD Model with $\dot{J}(t)$ Known  7
1.2.3.2 Euler-Type DTZD Model with $\dot{J}(t)$ Unknown  7
1.2.3.3 Taylor-Type DTZD Models  8
1.3 ZD Applications to Different-Type Robot Manipulators  9
1.3.1 Application to a Five-Link Planar Robot Manipulator  9
1.3.2 Application to a Three-Link Planar Robot Manipulator  12
1.4 Chapter Summary  14

Part II  Inverse-Free Simple Approach  15

2  G1 Type Scheme to JVL Inverse Kinematics  17
2.1 Introduction  17
2.2 Preliminaries and Related Work  18
2.3 Scheme Formulation  18
2.4 Computer Simulations  19
2.4.1 Square-Path Tracking Task  19
2.4.2 “Z”-Shaped Path Tracking Task  22
2.5 Physical Experiments  25
2.6 Chapter Summary  26
Contents

3 D1G1 Type Scheme to JAL Inverse Kinematics  27
  3.1 Introduction  27
  3.2 Preliminaries and Related Work  28
  3.3 Scheme Formulation  28
  3.4 Computer Simulations  29
  3.4.1 Rhombus-Path Tracking Task  29
    3.4.1.1 Verifications  29
    3.4.1.2 Comparisons  30
  3.4.2 Triangle-Path Tracking Task  32
  3.5 Chapter Summary  36

4 Z1G1 Type Scheme to JAL Inverse Kinematics  37
  4.1 Introduction  37
  4.2 Problem Formulation and Z1G1 Type Scheme  37
  4.3 Computer Simulations  38
    4.3.1 Desired Initial Position  38
      4.3.1.1 Isosceles-Trapezoid Path Tracking  40
      4.3.1.2 Isosceles-Triangle Path Tracking  41
      4.3.1.3 Square Path Tracking  42
  4.3.2 Nondesired Initial Position  44
  4.4 Physical Experiments  45
  4.5 Chapter Summary  45

Part III  QP Approach and Unification  47

5 Redundancy Resolution via QP Approach and Unification  49
  5.1 Introduction  49
  5.2 Robotic Formulation  50
  5.3 Handling Joint Physical Limits  52
    5.3.1 Joint-Velocity Level  52
    5.3.2 Joint-Acceleration Level  52
  5.4 Avoiding Obstacles  53
  5.5 Various Performance Indices  54
    5.5.1 Resolved at Joint-Velocity Level  55
      5.5.1.1 MVN scheme  55
      5.5.1.2 RMP scheme  55
      5.5.1.3 MKE scheme  55
    5.5.2 Resolved at Joint-Acceleration Level  55
      5.5.2.1 MAN scheme  55
      5.5.2.2 MTN scheme  56
      5.5.2.3 IIWT scheme  56
  5.6 Unified QP Formulation  56
  5.7 Online QP Solutions  57
    5.7.1 Traditional QP Routines  57
5.7.2 Compact QP Method 57
5.7.3 Dual Neural Network 57
5.7.4 LVI-Aided Primal-Dual Neural Network 57
5.7.5 Numerical Algorithms E47 and 94LVI 59
5.7.5.1 Numerical Algorithm E47 59
5.7.5.2 Numerical Algorithm 94LVI 59
5.8 Computer Simulations 61
5.9 Chapter Summary 66

Part IV Illustrative JVL QP Schemes and Performances 67

6 Varying Joint-Velocity Limits Handled by QP 69
6.1 Introduction 69
6.2 Preliminaries and Problem Formulation 70
6.2.1 Six-DOF Planar Robot System 70
6.2.2 Varying Joint-Velocity Limits 73
6.3 94LVI Assisted QP Solution 76
6.4 Computer Simulations and Physical Experiments 77
6.4.1 Line-Segment Path-Tracking Task 77
6.4.2 Elliptical-Path Tracking Task 85
6.4.3 Simulations with Faster Tasks 87
6.4.3.1 Line-Segment-Path-Tracking Task 87
6.4.3.2 Elliptical-Path-Tracking Task 89
6.5 Chapter Summary 92

7 Feedback-Aided Minimum Joint Motion 95
7.1 Introduction 95
7.2 Preliminaries and Problem Formulation 97
7.2.1 Minimum Joint Motion Performance Index 97
7.2.2 Varying Joint-Velocity Limits 100
7.3 Computer Simulations and Physical Experiments 101
7.3.1 “M”-Shaped Path-Tracking Task 101
7.3.1.1 Simulation Comparisons with Different $\kappa_p$ 101
7.3.1.2 Simulation Comparisons with Different $\gamma$ 103
7.3.1.3 Simulative and Experimental Verifications of FAMJM Scheme 105
7.3.2 “P”-Shaped Path Tracking Task 107
7.3.3 Comparisons with Pseudoinverse-Based Approach 108
7.3.3.1 Comparison with Tracking Task of Larger “M”-Shaped Path 110
7.3.3.2 Comparison with Tracking Task of Larger “P”-Shaped Path 112
7.4 Chapter Summary 119

8 QP Based Manipulator State Adjustment 121
8.1 Introduction 121
8.2 Preliminaries and Scheme Formulation 122
Part VI  Manipulability Maximization  199

12  Manipulability-Maximizing SMP Scheme  201
12.1  Introduction  201
12.2  Scheme Formulation  202
12.2.1  Derivation of Manipulability Index  202
12.2.2  Handling Physical Limits  203
12.2.3  QP Formulation  203
12.3  Computer Simulations and Physical Experiments  204
12.3.1  Computer Simulations  204
12.3.2  Physical Experiments  205
12.4  Chapter Summary  209

13  Time-Varying Coefficient Aided MM Scheme  211
13.1  Introduction  211
13.2  Manipulability-Maximization with Time-Varying Coefficient  212
13.2.1  Nonzero Initial/Final Joint-Velocity Problem  212
13.2.2  Scheme Formulation  213
13.2.3  94LVI Assisted QP Solution  215
13.3  Computer Simulations and Physical Experiments  216
13.3.1  Computer Simulations  216
13.3.2  Physical Experiments  224
13.4  Chapter Summary  226

Part VII  Encoder Feedback and Joystick Control  227

14  QP Based Encoder Feedback Control  229
14.1  Introduction  229
14.2  Preliminaries and Scheme Formulation  231
14.2.1  Joint Description  231
14.2.2  OMPFC Scheme  231
14.3  Computer Simulations  234
14.3.1  Petal-Shaped Path-Tracking Task  234
14.3.2  Comparative Simulations  238
14.3.2.1  Petal-Shaped Path Tracking Using Another Group of Joint-Angle Limits  238
14.3.2.2  Petal-Shaped Path Tracking via the Method 4 (M4) Algorithm  238
14.3.3  Hexagonal-Path-Tracking Task  239
14.4  Physical Experiments  240
14.5  Chapter Summary  248

15  QP Based Joystick Control  251
15.1  Introduction  251
15.2  Preliminaries and Hardware System  251
15.2.1  Velocity-Specified Inverse Kinematics Problem  252
15.2.2  Joystick-Controlled Manipulator Hardware System  252
Contents

15.3 Scheme Formulation  253
  15.3.1 Cosine-Aided Position-to-Velocity Mapping  253
  15.3.2 Real-Time Joystick-Controlled Motion Planning  254
15.4 Computer Simulations and Physical Experiments  254
  15.4.1 Movement Toward Four Directions  255
  15.4.2 “MVN” Letter Writing  259
15.5 Chapter Summary  259

References  261

Index  277