

Table of Contents

About the Authorxiii

About the Technical Reviewer xv

Preface xvii

Chapter 1: Industrial Robots.....1

 Nomenclature.....2

 Mechanical Configurations6

 Structure of a Robot Control System 11

 Digital Twin..... 14

 Summary..... 17

Part I: Robot Geometry 19

Chapter 2: Geometrical Framework.....21

 Reference Frames.....21

 Frame Operations.....24

 Frame Translations.....26

 Frame Rotations.....27

 Properties of a Rotation Matrix31

 Composing Rotations: Euler Angles32

 Decomposing a Rotation Matrix.....34

 Column Vectors36

 Expressing Rotations38

TABLE OF CONTENTS

Combining Translations and Rotations	39
Example	43
Inverted Transformation	46
Summary.....	48
Chapter 3: Forward Kinematics	49
Mechanical Structure.....	50
Step-by-Step Solution.....	54
Combined Transformation Matrix.....	60
Numerical Test	62
Zero Frame.....	66
Tool Frame	69
Mechanical Coupling.....	70
Summary.....	73
Chapter 4: Inverse Kinematics	75
Closed-Form Derivation	76
Nonlinear Problem	78
Nonunique Solution.....	79
Singularities	82
IK Step 1: Decoupling.....	85
IK Step 2: Solve the Arm	87
IK Step 3: Solve the Wrist.....	92
Numerical Test	96
Zero Frame.....	100
Tool Frame	101
Mechanical Coupling.....	103
Summary.....	104

Part II: Robot Movements	105
Chapter 5: Path-Planning	107
PTP Movements	109
Path Movements	113
Quaternions.....	115
SLERP	119
Line	124
Circle.....	125
Spline	129
De Casteljau's Algorithm	136
Round Edges	138
Transitions.....	142
Path Length.....	146
External Path Corrections	148
Summary.....	149
Chapter 6: Workspace Monitoring	151
Linearization	154
Safe Zones	157
Forbidden Zones	158
Wire-frame Model	161
Safe Orientation	163
Self-Collision.....	165
Capsules	167
Exclusive Zones	170
Collision Detection	173
Summary.....	179

TABLE OF CONTENTS

Chapter 7: Trajectory Generator181

S-Curve Profile..... 183

Sinusoidal Profile 195

Bezier Profile..... 199

Time-Optimal Movements..... 203

Differential Kinematics..... 208

Path Speed Definitions..... 211

Optimal Motion in Practice..... 214

Time Filtering 217

External Path Corrections 222

Summary..... 225

Chapter 8: Statics and Dynamics227

Statics 227

Singularities 232

Dynamics 236

Dynamic Model 240

Lagrangian Method 242

Newton-Euler Method 245

Parameters Identification..... 247

Torque Feed-Forward..... 250

Trajectory Optimization 252

Teach by Hand..... 255

Motor Sizing..... 258

Summary..... 260

Part III: Robot Software	263
Chapter 9: Firmware.....	265
Human-Machine Interface	266
Interpreter	271
Main Controller	285
Kernel Interface	294
Servo Drives.....	299
Electronic Commutation.....	305
Summary.....	323
Chapter 10: Calibration.....	325
Robot Calibration.....	326
Tool Calibration	330
Cell Calibration.....	338
Summary.....	344
Chapter 11: Commissioning	345
Safety.....	345
Tuning	352
Summary.....	364
Chapter 12: Simulation	367
Unity 3D.....	367
Building a Scene	369
Importing CAD Models	371
Programming Scripts	373
Communication Functions	377
User Interface	379

TABLE OF CONTENTS

Machine Learning	380
Summary.....	388
Chapter 13: Machine Vision.....	389
Smart Camera	391
Vision Functions.....	397
Deep Learning.....	404
Convolutional Networks	412
Summary.....	419
Part IV: Robot Hardware	423
Chapter 14: Motors.....	425
DC Motors	429
Stepper Motors	431
Brushless Motors	433
Linear Motors	437
Motor Sizing.....	441
Summary.....	449
Chapter 15: Encoders	451
Hall Sensors	455
Quadrature	457
SSI.....	461
Tamagawa.....	464
Summary.....	467
Chapter 16: Servo Drives	469
Power Switches	473
Gate Driver	482

TABLE OF CONTENTS

Current Sensing	488
Summary.....	497
Chapter 17: Power Management	499
DC Bus Voltage.....	500
Protection Functions	508
Voltage Converter.....	516
Summary.....	517
Chapter 18: Main Controller	519
Microcontroller.....	519
IOs.....	522
Fieldbus	528
Integrated Solution.....	530
Display	534
Summary.....	536
Chapter 19: Fabrication	537
PCB Design.....	537
Mechanics.....	548
Summary.....	551
Appendix: Kinematic Models	553
Index.....	601