
CONTENTS

1

INTRODUCTION	1
1.1 Background	1
1.2 The mechanics and control of mechanical manipulators	4
1.3 Notation	16

2

SPATIAL DESCRIPTIONS AND TRANSFORMATIONS	19
2.1 Introduction	19
2.2 Descriptions: positions, orientations, and frames	20
2.3 Mappings: changing descriptions from frame to frame	25
2.4 Operators: translations, rotations, transformations	32
2.5 Summary of interpretations	37
2.6 Transformation arithmetic	37
2.7 Transform equations	40
2.8 More on representation of orientation	43
2.9 Transformation of free vectors	56
2.10 Computational considerations	59

3

MANIPULATOR KINEMATICS	68
3.1 Introduction	68
3.2 Link description	69
3.3 Link connection description	72
3.4 Convention for affixing frames to links	75
3.5 Manipulator kinematics	83
3.6 Actuator space, joint space, and Cartesian space	85
3.7 Examples: kinematics of two industrial robots	86
3.8 Frames with standard names	99
3.9 WHERE is the tool?	102
3.10 Computational considerations	102

4

INVERSE MANIPULATOR KINEMATICS	113
4.1 Introduction	113
4.2 Solvability	114
4.3 The notion of manipulator subspace when $n < 6$	120
4.4 Algebraic vs. geometric	122
4.5 Algebraic solution by reduction to polynomial	128
4.6 Pieper's solution when three axes intersect	129
4.7 Examples of inverse manipulator kinematics	131
4.8 The standard frames	141
4.9 SOLVE-ing a manipulator	143
4.10 Repeatability and accuracy	143
4.11 Computational considerations	144

5

JACOBIANS: VELOCITIES AND STATIC FORCES	152
5.1 Introduction	152
5.2 Notation for time-varying position and orientation	153
5.3 Linear and rotational velocity of rigid bodies	156
5.4 More on angular velocity	159
5.5 Motion of the links of a robot	164
5.6 Velocity "propagation" from link to link	165
5.7 Jacobians	169
5.8 Singularities	173
5.9 Static forces in manipulators	175
5.10 Jacobians in the force domain	179
5.11 Cartesian transformation of velocities and static forces	180

6

MANIPULATOR DYNAMICS	187
6.1 Introduction	187
6.2 Acceleration of a rigid body	188

6.3	Mass distribution	190
6.4	Newton's equation, Euler's equation	195
6.5	Iterative Newton-Euler dynamic formulation	196
6.6	Iterative vs. closed form	201
6.7	An example of closed form dynamic equations	201
6.8	The structure of the manipulator dynamic equations	205
6.9	Lagrangian formulation of manipulator dynamics	207
6.10	Formulating manipulator dynamics in Cartesian space	211
6.11	Inclusion of nonrigid body effects	214
6.12	Dynamic simulation	215
6.13	Computational considerations	216

7

	TRAJECTORY GENERATION	227
7.1	Introduction	227
7.2	General considerations in path description and generation	228
7.3	Joint space schemes	230
7.4	Cartesian space schemes	246
7.5	Geometric problems with Cartesian paths	249
7.6	Path Generation at Run Time	252
7.7	Description of paths with a robot programming language	255
7.8	Planning paths using the dynamic model	255
7.9	Collision-free path planning	256

8

	MANIPULATOR MECHANISM DESIGN	262
8.1	Introduction	262
8.2	Basing the design on task requirements	263
8.3	Kinematic configuration	267
8.4	Quantitative measures of workspace attributes	273
8.5	Redundant and closed chain structures	277
8.6	Actuation schemes	280
8.7	Stiffness and deflections	283
8.8	Position sensing	289
8.9	Force sensing	290

9

	LINEAR CONTROL OF MANIPULATORS	299
9.1	Introduction	299
9.2	Feedback and closed loop control	300
9.3	Second-order linear systems	302
9.4	Control of second-order systems	310
9.5	Control law partitioning	312
9.6	Trajectory-following control	315

9.7	Disturbance rejection	316
9.8	Continuous vs. discrete time control	318
9.9	Modeling and control of a single joint	319
9.10	Architecture of an industrial robot controller	326

10

NONLINEAR CONTROL OF MANIPULATORS		332
10.1	Introduction	332
10.2	Nonlinear and time-varying systems	333
10.3	Multi-input, multi-output control systems	338
10.4	The control problem for manipulators	338
10.5	Practical considerations	340
10.6	Present industrial robot control systems	346
10.7	Lyapunov stability analysis	348
10.8	Cartesian-based control systems	353
10.9	Adaptive control	359

11

FORCE CONTROL OF MANIPULATORS		365
11.1	Introduction	365
11.2	Application of industrial robots to assembly tasks	366
11.3	A framework for control in partially constrained tasks	367
11.4	The hybrid position/force control problem	373
11.5	Force control of a mass-spring	374
11.6	The hybrid position/force control scheme	378
11.7	Present industrial robot control schemes	384

12

ROBOT PROGRAMMING LANGUAGES AND SYSTEMS		390
12.1	Introduction	390
12.2	The three levels of robot programming	391
12.3	A sample application	394
12.4	Requirements of a robot programming language	396
12.5	An example application coded in three RPLs	401
12.6	Problems peculiar to robot programming languages	407

13

OFF-LINE PROGRAMMING SYSTEMS		414
13.1	Introduction	414
13.2	Central issues in OLP systems	417
13.3	CimStation	423
13.4	Automating subtasks in OLP systems	435
13.5	Summary	437

Appendices

A	TRIGONOMETRIC IDENTITIES	440
B	THE TWENTY-FOUR ANGLE SET CONVENTIONS	442
C	SOME INVERSE KINEMATIC FORMULAS	445
INDEX		447