

# CONTENTS

List of Figures . . . . .	xi
List of Tables . . . . .	xv
Series Foreword . . . . .	xvii
Preface . . . . .	xix
Acknowledgments . . . . .	xxvii

## SECTION I—*Kinematic and Force Analysis of Articulated Hands*

—J.K. Salisbury, Jr.

Nomenclature . . . . .	2
------------------------	---

### **Chapter 1 Introduction**

1.0 Robots - Fact and Fiction . . . . .	3
1.1 Overview of Existing Hands . . . . .	4
1.2 Preview . . . . .	5

### **Chapter 2 Contact - Freedom and Constraint**

2.0 Introduction . . . . .	9
2.1 Contact . . . . .	11
2.2 Types of Contact Between Bodies . . . . .	12
2.3 Effect of Single Contacts Between Bodies . . . . .	14
2.4 Screws, Twists and Wrenches . . . . .	15
2.5 Geometry of Contact Twist and Wrench Systems . . . . .	19

### **Chapter 3 Number Synthesis of Hands**

3.0 Introduction . . . . .	25
3.1 Mobility and Connectivity . . . . .	26
3.2 Enumeration of Hand Mechanisms . . . . .	27

### **Chapter 4 Contacts in Groups**

4.0 Introduction . . . . .	33
4.1 Constraint by Groups of Contacts . . . . .	34
4.1.1 3-Freedom Contact . . . . .	34
4.1.2 4-Freedom Contact . . . . .	36
4.1.3 5-Freedom Contact . . . . .	37

### **Chapter 5 Complete Restraint and Internal Forces**

5.0 Introduction . . . . .	39
5.1 Algebraic Approach . . . . .	40

5.2	Geometric Approach . . . . .	44
<b>Chapter 6</b>	<b>Force Application and Velocity Analysis</b>	
6.0	Introduction . . . . .	49
6.1	The Grip Transform, $G$ . . . . .	50
6.2	Control and Sensing of External and Internal Forces .	51
6.3	Control and Sensing of Velocities . . . . .	52
<b>Chapter 7</b>	<b>Stiffness Control and Sensing</b>	
7.0	Introduction . . . . .	55
7.1	Review of Force Control . . . . .	56
7.2	Stiffness Control . . . . .	59
7.3	Stiffness Sensing . . . . .	63
7.4	Conclusions . . . . .	64
<b>Chapter 8</b>	<b>Force Error Analysis</b>	
8.0	Introduction . . . . .	65
8.1	Effect of Structural Stiffness on Force Accuracy . . .	65
8.2	Force Error Propagation . . . . .	68
8.3	Isotropic Points in a Two-link Mechanism . . . . .	69
8.4	Isotropic Points in a Three-link Mechanism . . . . .	74
8.5	Conclusions . . . . .	76
<b>Chapter 9</b>	<b>Conclusions</b>	
9.0	Review . . . . .	77
9.1	Stanford/JPL Hand . . . . .	78
9.2	The Future . . . . .	87
References	. . . . .	90
Appendix	. . . . .	94
	<i>Active Stiffness Control of a Manipulator</i>	
	<i>in Cartesian Coordinates . . . . .</i>	95
	<i>Articulated Hands: Force Control and Kinematic Issues . .</i>	109
	<i>Interpretation of Contact Geometries</i>	
	<i>from Force Measurements . . . . .</i>	133
	<i>Design and Control of an Articulated Hand . . . . .</i>	151

SECTION II—*Manipulator Grasping and Pushing Operations*

—M.T. Mason

<b>Chapter 1</b>	<b>Introduction</b> . . . . .	171
1.1	Analysis of an Example Grasping Motion . . . . .	172
1.2	Discussion . . . . .	179
1.3	Overview . . . . .	183
1.4	Previous Work . . . . .	184
<b>Chapter 2</b>	<b>Theory of Pushing</b> . . . . .	189
2.1	Friction of Planar Motion . . . . .	192
2.2	Pushing with Fixed or Rolling Contact . . . . .	201
2.3	Pushing with Sliding Contact . . . . .	221
2.4	Undetermined Contact Mode . . . . .	236
2.5	On Quasi-static Analysis . . . . .	244
<b>Chapter 3</b>	<b>Application</b> . . . . .	253
3.1	Automatic Orientation . . . . .	253
3.2	Automatic Planning of Grasping . . . . .	261
3.3	Verification of Grasping . . . . .	263
<b>Chapter 4</b>	<b>Conclusion</b> . . . . .	271
Table 1	. . . . .	273
Appendix	. . . . .	275
References	. . . . .	287
Index	. . . . .	295