

# CONTENTS

## 1

INTRODUCTION	1
1.1 Introduction	1
1.2 Historical Summary	2
1.3 Contributions of this Book	4
1.4 Preview of the Book	5

## 2

CONTROL OF MECHANICAL MANIPULATORS	7
2.1 Introduction	7
2.2 Structure of the Manipulator Dynamic Equations	8
2.2.1 The Manipulator Mass Matrix	10
2.2.2 The Centrifugal and Coriolis Terms	12
2.2.3 The Friction Terms	14
2.2.4 The Gravity Terms	14
2.3 The Control Method of Arimoto	15
2.4 Nonlinear Model-Based Control of Manipulators	16

## 3

ROBUSTNESS OF MODEL-BASED CONTROL OF MANIPULATORS	19
3.1 Introduction	19
3.2 Previous Related Work	20
3.3 Error Equation with Parameter Mismatch	21
3.4 An Approach to Robustness Analysis	25
3.5 Statement of Robustness Theorem 3.1	30
3.6 Numerical Example of Theorem 3.1	31
3.7 A Robustness Conjecture	33

<b>4</b>		
	REVIEW OF ADAPTIVE CONTROL	37
4.1	Introduction	37
4.2	Model Reference Adaptive Control	38
4.3	Review of Previous Work in Adaptive Manipulator Control	44
4.4	Conclusion	47
<b>5</b>		
	ADAPTIVE CONTROL OF MANIPULATORS	49
5.1	Introduction	49
5.2	The Dynamic Model of a Manipulator	50
5.3	Nonlinear Model-Based Control	51
5.4	The Error Equation	53
5.5	The Adaptation Algorithm	55
5.6	Parameter Error Convergence	58
5.7	Robustness to Bounded Disturbances	60
5.8	Simulation Results	63
5.9	Experimental Results	74
	5.9.1 Dynamics of the Adept One	74
	5.9.2 Experimental Implementation	76
	5.9.3 Experimental Results	79
<b>6</b>		
	LEARNING CONTROL OF MANIPULATORS	85
6.1	Introduction	85
6.2	Previous Research	86
6.3	Background	86
6.4	Outline of the Method	88
6.5	The Control Law and Error Equation	89
6.6	Convergence	90
6.7	Simulation Results	93
<b>7</b>		
	CONCLUSIONS	101
7.1	Robustness	101
7.2	Adaptive Control	101
7.3	Learning Control	102

<b>A</b>		
NORMS AND NORMED SPACES		105
A.1	Introduction	105
A.2	Vector Norms	105
A.3	Induced Matrix Norms	106
A.4	Function Norms	107
A.5	Operator Gains	108
A.6	L-Infinity Function Norms and Operator Gains	108
<b>B</b>		
LYAPUNOV STABILITY THEORY		111
B.1	Introduction	111
B.2	Lyapunov's Direct Method	111
B.3	LaSalle's Extension: Invariant Sets	112
B.4	Illustrative Examples	112
<b>C</b>		
STRICTLY POSITIVE REAL SYSTEMS		115
C.1	Introduction	115
C.2	Frequency-Domain Definition	115
C.3	Engineering Definition	115
C.4	Time-Domain Definition	116
C.5	State-Space Definition	
References		117
INDEX		137