

# CONTENTS

<b>Preface</b>	<b>xiii</b>
<b>Contributors</b>	<b>xvii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Early History of Fuzzy Control	1
1.2 What Is a Type-1 Fuzzy Set?	2
1.3 What Is a Type-1 Fuzzy Logic Controller?	3
1.4 What Is a Type-2 Fuzzy Set?	7
1.5 What Is a Type-2 Fuzzy Logic Controller?	9
1.6 Distinguishing an FLC from Other Nonlinear Controllers	10
1.7 T2 FLCs versus T1 FLCs	11
1.8 Real-World Applications of IT2 Mamdani FLCs	14
1.8.1 Applications to Industrial Control	14
1.8.2 Airplane Altitude Control	23
1.8.3 Control of Mobile Robots	24
1.8.4 Control of Ambient Intelligent Environments	27
1.9 Book Rationale	29
1.10 Software and How it Can Be Accessed	30
1.11 Coverage of the Other Chapters	30
<b>2 Introduction to Type-2 Fuzzy Sets</b>	<b>32</b>
2.1 Introduction	32
2.2 Brief Review of Type-1 Fuzzy Sets	32
2.2.1 Some Definitions	32
2.2.2 Set-Theoretic Operations	35
2.2.3 Alpha Cuts	36
2.2.4 Compositions of T1 FSs	39
2.2.5 Rules and Their MFs	40
2.3 Interval Type-2 Fuzzy Sets	42
2.3.1 Introduction	42

2.3.2	Definitions	43
2.3.3	Set-Theoretic Operations	51
2.3.4	Centroid of an IT2 FS	54
2.3.5	Properties of $c_l(k)$ and $c_r(k)$	58
2.3.6	KM Algorithms as Well as Some Others	59
2.4	General Type-2 Fuzzy Sets	68
2.4.1	$\alpha$ -Plane/zSlice Representation	68
2.4.2	Set-Theoretic Operations	72
2.4.3	Centroid of a GT2 FS	73
2.5	Wrapup	77
2.6	Moving On	79
<b>3</b>	<b>Interval Type-2 Fuzzy Logic Controllers</b>	<b>80</b>
3.1	Introduction	80
3.2	Type-1 Fuzzy Logic Controllers	80
3.2.1	Introduction	80
3.2.2	T1 Mamdani FLCs	81
3.2.3	T1 TSK FLCs	85
3.2.4	Design of T1 FLCs	86
3.3	Interval Type-2 Fuzzy Logic Controllers	86
3.3.1	Introduction	86
3.3.2	IT2 Mamdani FLCs	87
3.3.3	IT2 TSK FLCs	103
3.3.4	Design of T2 FLCs	105
3.4	Wu–Mendel Uncertainty Bounds	105
3.5	Control Analyses of IT2 FLCs	111
3.6	Determining the FOU Parameters of IT2 FLCs	114
3.6.1	Blurring T1 MFs	114
3.6.2	Optimizing FOU Parameters	114
3.7	Moving On	122
	Appendix 3A. Proof of Theorem 3.4	123
3A.1	Inner-Bound Set $[\bar{u}_l(\mathbf{x}), \underline{u}_r(\mathbf{x})]$	123
3A.2	Outer-Bound Set $[\underline{u}_l(\mathbf{x}), \bar{u}_r(\mathbf{x})]$	124
<b>4</b>	<b>Analytical Structure of Various Interval Type-2 Fuzzy PI and PD Controllers</b>	<b>131</b>
4.1	Introduction	131
4.2	PID, PI, and PD Controllers and Their Relationships	134

4.2.1	Two Forms of PID Controller—Position Form and Incremental Form	134
4.2.2	PI and PD Controllers and Their Relationship	135
4.3	Components of the Interval T2 Fuzzy PI and PD Controllers	136
4.4	Mamdani Fuzzy PI and PD Controllers—Configuration 1	140
4.4.1	Fuzzy PI Controller Configuration	140
4.4.2	Method for Deriving the Analytical Structure	144
4.5	Mamdani Fuzzy PI and PD Controllers—Configuration 2	154
4.6	Mamdani Fuzzy PI and PD Controllers—Configuration 3	162
4.6.1	Fuzzy PI Controller Configuration	162
4.6.2	Method for Deriving the Analytical Structure	165
4.7	Mamdani Fuzzy PI and PD Controllers—Configuration 4	169
4.7.1	Fuzzy PI Controller Configuration	169
4.7.2	Method for Deriving the Analytical Structure	171
4.8	TSK Fuzzy PI and PD Controllers—Configuration 5	181
4.8.1	Fuzzy PI Controller Configuration	181
4.8.2	Deriving the Analytical Structure	184
4.9	Analyzing the Derived Analytical Structures	185
4.9.1	Structural Connection with the Corresponding T1 Fuzzy PI Controller	186
4.9.2	Characteristics of the Variable Gains of the T2 Fuzzy PI Controller	190
4.10	Design Guidelines for the T2 Fuzzy PI and PD Controllers	194
4.10.1	Determination of $\theta_1$ and $\theta_2$ Values	196
4.10.2	Determination of the Remaining Nine Parameter Values	197
4.11	Summary	198
	Appendix 4A	200
<b>5</b>	<b>Analysis of Simplified Interval Type-2 Fuzzy PI and PD Controllers</b>	<b>205</b>
5.1	Introduction	205
5.2	Simplified Type-2 FLCs: Design, Computation, and Performance	206
5.2.1	Structure of a Simplified IT2 FLC	207
5.2.2	Output Computation	208
5.2.3	Computational Cost	209
5.2.4	Genetic Tuning of FLC	210

5.2.5	Performance	211
5.2.6	Discussions	216
5.3	Analytical Structure of Interval T2 Fuzzy PD and PI Controller	221
5.3.1	Configuration of Interval T2 Fuzzy PD and PI Controller	221
5.3.2	Analysis of the Karnik–Mendel Type-Reduced IT2 Fuzzy PD Controller	227
5.3.3	Analysis of the IT2 Fuzzy PD Controller	231
5.4	Conclusions	248
<b>6</b>	<b>On the Design of IT2 TSK FLCs</b>	<b>251</b>
6.1	Introduction	251
6.2	Preliminaries	251
6.2.1	Discrete T1 TSK FLC: Rules and Firing Level	252
6.2.2	Continuous T1 TSK FLC: Rules and Firing Level	252
6.2.3	T1 TSK FLC Output	253
6.2.4	Discrete IT2 TSK FLC: Rules and Firing Interval	253
6.2.5	Continuous IT2 TSK FLC: Rules and Firing Interval	253
6.2.6	IT2 TSK FLC Output	254
6.3	Novel Inference Engine for Control Design	254
6.4	Stability of IT2 TSK FLCs	255
6.4.1	Stability of Discrete IT2 TSK FLC	255
6.4.2	Stability of Continuous IT2 TSK FLC	258
6.4.3	Examples	259
6.5	Design of Adaptive IT2 TSK FLC	264
6.5.1	Rule Bases	264
6.5.2	Membership Functions	265
6.5.3	Control Structure	265
6.5.4	Control Design	266
6.5.5	Control Performance	267
6.6	Adaptive Control Design with Application to Robot Manipulators	268
6.6.1	Tracking Control	269
6.6.2	Control Structure	270
6.6.3	Application to Modular and Reconfigurable Robot Manipulators (MRR)	274

6.7	Robust Control Design	277
6.7.1	System Description	277
6.7.2	Disturbance Rejection Problem and Solution	280
6.7.3	Robust Control Example	284
6.8	Summary	285
	Appendix	285
<b>7</b>	<b>Looking into the Future</b>	<b>290</b>
7.1	Introduction	290
7.2	William Melek and Hao Ying Look into the Future	290
7.3	Hani Hagrass Looks into the Future	293
7.3.1	Nonsingleton IT2 FL Control	293
7.3.2	zSlices-Based Singleton General T2 FL Control	299
7.4	Woei Wan Tan Looks into the Future	306
7.5	Jerry Mendel Looks into The Future	307
7.5.1	IT2 FLC	307
7.5.2	GT2 FLC	309
	<b>Appendix A T2 FLC Software: From Type-1 to zSlices-Based General Type-2 FLCs</b>	<b>315</b>
A.1	Introduction	315
A.2	FLC for Right-Edge Following	315
A.3	Type-1 FLC Software	316
A.3.1	Define and Set Up T1 FLC Inputs	316
A.3.2	Define T1 FSs That Quantify Each Variable	316
A.3.3	Define Logical Antecedents and Consequents for the FL Rules	318
A.3.4	Define Rule Base of T1 FLC	318
A.4	Interval T2 FLC Software	321
A.4.1	Define and Set Up FLC Inputs	323
A.4.2	Define IT2 FSs That Quantify Each Variable	323
A.4.3	Define Logical Antecedents and Consequents for the FL Rules	323
A.4.4	Define Rule Base of the IT2 FLC	323
A.5	zSlices-Based General Type-2 FLC Software	327
A.5.1	Define and Set Up FLC Inputs	327

