

Table of Contents

Preface - Second Edition	xv
Preface	xvii
Organization of Book	xxi
1 Systems and Models	1
1.1 INTRODUCTION	1
1.2 SYSTEM AND CONTROL BASICS	2
1.2.1 The Concept of System	2
1.2.2 The Input-Output Modeling Process	2
1.2.3 The Concept of State	6
1.2.4 The State Space Modeling Process	8
1.2.5 Sample Paths of Dynamic Systems	13
1.2.6 State Spaces	15
1.2.7 The Concept of Control	20
1.2.8 The Concept of Feedback	22
1.2.9 Discrete-Time Systems	25
1.3 DISCRETE EVENT SYSTEMS	26
1.3.1 The Concept of Event	27
1.3.2 Characteristic Properties of Discrete Event Systems	30
1.3.3 The Three Levels of Abstraction in the Study of Discrete Event Systems	33
1.3.4 Examples of Discrete Event Systems	35
1.3.5 Hybrid Systems	43
1.4 SUMMARY OF SYSTEM CLASSIFICATIONS	44
1.5 THE GOALS OF SYSTEM THEORY	46
SUMMARY	48
PROBLEMS	48
SELECTED REFERENCES	50
2 Languages and Automata	53
2.1 INTRODUCTION	53
2.2 THE CONCEPTS OF LANGUAGES AND AUTOMATA	54
2.2.1 Language Models of Discrete-Event Systems	54
2.2.2 Automata	59
2.2.3 Languages Represented by Automata	62
2.2.4 Nondeterministic Automata	69
2.2.5 Automata with Inputs and Outputs	72

2.3	OPERATIONS ON AUTOMATA	74
2.3.1	Unary Operations	75
2.3.2	Composition Operations	77
2.3.3	State Space Refinement	85
2.3.4	Observer Automata	87
2.3.5	Equivalence of Automata	90
2.4	FINITE-STATE AUTOMATA	92
2.4.1	Definition and Properties of Regular Languages	92
2.4.2	Regular Expressions	95
2.4.3	State Space Minimization	96
2.5	ANALYSIS OF DISCRETE-EVENT SYSTEMS	100
2.5.1	Safety and Blocking Properties	101
2.5.2	Partially-Observed DES	102
2.5.3	Event Diagnosis	108
2.5.4	Software Tools and Computational Complexity Issues	117
2.5.5	Formal Verification and Model Checking	118
	SUMMARY	119
	PROBLEMS	120
	SELECTED REFERENCES	130

3 Supervisory Control 133

3.1	INTRODUCTION	133
3.2	FEEDBACK CONTROL WITH SUPERVISORS	135
3.2.1	Controlled Discrete Event Systems	135
3.2.2	Control Under Partial Observation	137
3.3	SPECIFICATIONS ON CONTROLLED SYSTEM	139
3.3.1	Modeling of Specifications as Automata	140
3.3.2	The Need for Formal Methods	143
3.4	CONTROL WITH PARTIAL CONTROLLABILITY	145
3.4.1	Controllability Theorem	145
3.4.2	Realization of Supervisors	148
3.4.3	The Property of Controllability	151
3.4.4	Some Supervisory Control Problems and Their Solutions	156
3.4.5	Computation of $K^{\uparrow C}$: Prefix-Closed Case	159
3.4.6	Computation of $K^{\downarrow C}$	161
3.5	NONBLOCKING CONTROL	163
3.5.1	Nonblocking Controllability Theorem	163
3.5.2	Nonblocking Supervisory Control	164
3.5.3	Computation of $K^{\downarrow C}$: General Case	167
3.5.4	Dealing with Blocking Supervisors	170
3.6	CONTROL WITH MODULAR SPECIFICATIONS	174
3.7	CONTROL UNDER PARTIAL OBSERVATION	178
3.7.1	Controllability and Observability Theorem	178
3.7.2	Realization of P-Supervisors	185
3.7.3	The Property of Observability	188
3.7.4	Supervisory Control Problems Under Partial Observation	193
3.7.5	The Property of Normality	195

3.8	DECENTRALIZED CONTROL	199
3.8.1	Conjunctive Architecture	201
3.8.2	Disjunctive Architecture	205
3.8.3	Combined Architecture	208
3.8.4	Realization of Decentralized Supervisors	210
3.8.5	The Property of Coobservability	210
3.8.6	Undecidability in Decentralized Control	211
	SUMMARY	212
	PROBLEMS	213
	SELECTED REFERENCES	219
4	Petri Nets	223
4.1	INTRODUCTION	223
4.2	PETRI NET BASICS	224
4.2.1	Petri Net Notation and Definitions	224
4.2.2	Petri Net Markings and State Spaces	226
4.2.3	Petri Net Dynamics	227
4.2.4	Petri Net Languages	231
4.2.5	Petri Net Models for Queueing Systems	233
4.3	COMPARISON OF PETRI NETS AND AUTOMATA	236
4.4	ANALYSIS OF PETRI NETS	239
4.4.1	Problem Classification	239
4.4.2	The Coverability Tree	244
4.4.3	Applications of the Coverability Tree	247
4.4.4	Linear-Algebraic Techniques	250
4.5	CONTROL OF PETRI NETS	253
4.5.1	Petri Nets and Supervisory Control Theory	254
4.5.2	State-Based Control of Petri Nets	257
	SUMMARY	260
	PROBLEMS	261
	SELECTED REFERENCES	266
5	Timed and Hybrid Models	269
5.1	INTRODUCTION	269
5.2	TIMED AUTOMATA	270
5.2.1	The Clock Structure	271
5.2.2	Event Timing Dynamics	275
5.2.3	A State Space Model	278
5.2.4	Queueing Systems as Timed Automata	283
5.2.5	The Event Scheduling Scheme	285
5.3	TIMED PETRI NETS	286
5.3.1	Timed Petri Net Dynamics	288
5.3.2	Queueing Systems as Timed Petri Nets	290
5.4	DIOD ALGEBRAS	292
5.4.1	Basic Properties of the $(\max, +)$ Algebra	292
5.4.2	Modeling Queueing Systems in the $(\max, +)$ Algebra	294
5.5	ALTERNATIVE TIMED MODELS	297

5.6	TIMED AUTOMATA WITH GUARDS	299
5.6.1	Model Definition	300
5.6.2	Model Execution	303
5.6.3	Parallel Composition	305
5.6.4	Untiming	307
5.7	HYBRID MODELS	311
5.7.1	Hybrid Automata	312
	SUMMARY	318
	PROBLEMS	319
	SELECTED REFERENCES	324

6 Stochastic Timed Automata 327

6.1	INTRODUCTION	327
6.2	STOCHASTIC PROCESS BASICS	328
6.2.1	Continuous-state and Discrete-state Stochastic Processes	329
6.2.2	Continuous-time and Discrete-time Stochastic Processes	329
6.2.3	Some Important Classes of Stochastic Processes	329
6.3	STOCHASTIC CLOCK STRUCTURES	333
6.4	STOCHASTIC TIMED AUTOMATA	334
6.5	THE GENERALIZED SEMI-MARKOV PROCESS	336
6.5.1	Queueing Systems as Stochastic Timed Automata	339
6.5.2	GSMP Analysis	340
6.6	THE POISSON COUNTING PROCESS	341
6.7	PROPERTIES OF THE POISSON PROCESS	347
6.7.1	Exponentially Distributed Interevent Times	347
6.7.2	The Memoryless Property	348
6.7.3	Superposition of Poisson Processes	351
6.7.4	The Residual Lifetime Paradox	353
6.8	AUTOMATA WITH POISSON CLOCK STRUCTURE	355
6.8.1	Distribution of Interevent Times	356
6.8.2	Distribution of Events	357
6.8.3	Markov Chains	359
6.9	EXTENSIONS OF THE GSMP	360
	SUMMARY	362
	PROBLEMS	364
	SELECTED REFERENCES	367

7 Markov Chains 369

7.1	INTRODUCTION	369
7.2	DISCRETE-TIME MARKOV CHAINS	370
7.2.1	Model Specification	370
7.2.2	Transition Probabilities and the Chapman-Kolmogorov Equations	371
7.2.3	Homogeneous Markov Chains	372
7.2.4	The Transition Probability Matrix	374
7.2.5	State Holding Times	377
7.2.6	State Probabilities	378
7.2.7	Transient Analysis	378
7.2.8	Classification of States	382

7.2.9	Steady State Analysis	391
7.2.10	Irreducible Markov Chains	392
7.2.11	Reducible Markov Chains	397
7.3	CONTINUOUS-TIME MARKOV CHAINS	399
7.3.1	Model Specification	400
7.3.2	Transition Functions	400
7.3.3	The Transition Rate Matrix	401
7.3.4	Homogeneous Markov Chains	402
7.3.5	State Holding Times	402
7.3.6	Physical Interpretation and Properties of the Transition Rate Matrix	403
7.3.7	Transition Probabilities	405
7.3.8	State Probabilities	407
7.3.9	Transient Analysis	407
7.3.10	Steady State Analysis	410
7.4	BIRTH-DEATH CHAINS	412
7.4.1	The Pure Birth Chain	414
7.4.2	The Poisson Process Revisited	415
7.4.3	Steady State Analysis of Birth-Death Chains	415
7.5	UNIFORMIZATION OF MARKOV CHAINS	417
	SUMMARY	421
	PROBLEMS	422
	SELECTED REFERENCES	427

8	Introduction to Queueing Theory	429
8.1	INTRODUCTION	429
8.2	SPECIFICATION OF QUEUEING MODELS	430
8.2.1	Stochastic Models for Arrival and Service Processes	430
8.2.2	Structural Parameters	431
8.2.3	Operating Policies	431
8.2.4	The $A/B/m/K$ Notation	432
8.2.5	Open and Closed Queueing Systems	434
8.3	PERFORMANCE OF A QUEUEING SYSTEM	434
8.4	QUEUEING SYSTEM DYNAMICS	437
8.5	LITTLE'S LAW	439
8.6	SIMPLE MARKOVIAN QUEUEING SYSTEMS	442
8.6.1	The $M/M/1$ Queueing System	444
8.6.2	The $M/M/m$ Queueing System	448
8.6.3	The $M/M/\infty$ Queueing System	452
8.6.4	The $M/M/1/K$ Queueing System	454
8.6.5	The $M/M/m/m$ Queueing System	458
8.6.6	The $M/M/1//N$ Queueing System	459
8.6.7	The $M/M/m/K/N$ Queueing System	461
8.7	MARKOVIAN QUEUEING NETWORKS	462
8.7.1	The Departure Process of the $M/M/1$ Queueing System	464
8.7.2	Open Queueing Networks	467
8.7.3	Closed Queueing Networks	471
8.7.4	Product Form Networks	476

8.8	NON-MARKOVIAN QUEUEING SYSTEMS	478
8.8.1	The Method of Stages	479
8.8.2	Mean Value Analysis of the $M/G/1$ Queueing System	482
8.8.3	Software Tools for the Analysis of General Queueing Networks	488
	SUMMARY	490
	PROBLEMS	491
	SELECTED REFERENCES	496
9	Controlled Markov Chains	499
9.1	INTRODUCTION	499
9.2	APPLYING "CONTROL" IN MARKOV CHAINS	500
9.3	MARKOV DECISION PROCESSES	502
9.3.1	Cost Criteria	503
9.3.2	Uniformization	504
9.3.3	The Basic Markov Decision Problem	506
9.4	SOLVING MARKOV DECISION PROBLEMS	510
9.4.1	The Basic Idea of Dynamic Programming	510
9.4.2	Dynamic Programming and the Optimality Equation	514
9.4.3	Extensions to Unbounded and Undiscounted Costs	524
9.4.4	Optimization of the Average Cost Criterion	532
9.5	CONTROL OF QUEUEING SYSTEMS	535
9.5.1	The Admission Problem	537
9.5.2	The Routing Problem	542
9.5.3	The Scheduling Problem	546
	SUMMARY	552
	PROBLEMS	553
	SELECTED REFERENCES	554
10	Introduction to Discrete-Event Simulation	557
10.1	INTRODUCTION	557
10.2	THE EVENT SCHEDULING SCHEME	558
10.2.1	Simulation of a Simple Queueing System	561
10.3	THE PROCESS-ORIENTED SIMULATION SCHEME	573
10.4	DISCRETE-EVENT SIMULATION LANGUAGES	574
10.5	RANDOM NUMBER GENERATION	576
10.5.1	The Linear Congruential Technique	577
10.6	RANDOM VARIATE GENERATION	578
10.6.1	The Inverse Transform Technique	579
10.6.2	The Convolution Technique	582
10.6.3	The Composition Technique	583
10.6.4	The Acceptance-Rejection Technique	583
10.7	OUTPUT ANALYSIS	587
10.7.1	Simulation Characterizations	587
10.7.2	Parameter Estimation	589
10.7.3	Output Analysis of Terminating Simulations	595
10.7.4	Output Analysis of Non-Terminating Simulations	598
	SUMMARY	604
	PROBLEMS	605
	SELECTED REFERENCES	614

11	Sensitivity Analysis and Concurrent Estimation	617
11.1	INTRODUCTION	617
11.2	SAMPLE FUNCTIONS AND THEIR DERIVATIVES	619
	11.2.1 Performance Sensitivities	620
	11.2.2 The Uses of Sensitivity Information	621
11.3	PERTURBATION ANALYSIS: SOME KEY IDEAS	623
11.4	PA OF $GI/G/1$ QUEUEING SYSTEMS	629
	11.4.1 Perturbation Generation	630
	11.4.2 Perturbation Propagation	634
	11.4.3 Infinitesimal Perturbation Analysis (IPA)	639
	11.4.4 Implementation of IPA for the $GI/G/1$ System	649
11.5	IPA FOR STOCHASTIC TIMED AUTOMATA	650
	11.5.1 Event Time Derivatives	652
	11.5.2 Sample Function Derivatives	655
	11.5.3 Performance Measure Derivatives	657
	11.5.4 IPA Applications	665
11.6	SENSITIVITY ESTIMATION REVISITED	670
11.7	EXTENSIONS OF IPA	673
	11.7.1 Discontinuities due to Multiple Customer Classes	673
	11.7.2 Discontinuities due to Routing Decisions	678
	11.7.3 Discontinuities due to Blocking: IPA with Event Rescheduling (RIPA)	680
11.8	SMOOTHED PERTURBATION ANALYSIS (SPA)	681
	11.8.1 Systems with Real-Time Constraints	685
	11.8.2 Marking and Phantomizing Techniques	687
11.9	IPA FOR STOCHASTIC HYBRID AUTOMATA	691
	11.9.1 Stochastic Fluid Models (SFMs)	693
	11.9.2 Sample paths of SFMs	695
	11.9.3 Comparing SFMs to Their DES Counterparts	697
	11.9.4 IPA for a Single-Class Single-Node SFM	700
	11.9.5 IPA for SFMs with Multiple Classes, Multiple Nodes and Feedback	705
11.10	PA FOR FINITE PARAMETER CHANGES	705
11.11	CONCURRENT ESTIMATION	706
	11.11.1 The Sample Path Constructability Problem	707
	11.11.2 Uses of Concurrent Estimation: “Rapid Learning”	709
	11.11.3 Sample Path Constructability Conditions	710
	11.11.4 The Standard Clock Approach	714
	11.11.5 Augmented System Analysis	718
	11.11.6 The “Time Warping” Algorithm	725
	SUMMARY	730
	PROBLEMS	732
	SELECTED REFERENCES	736
I	Review of Probability Theory	741
I.1	BASIC CONCEPTS AND DEFINITIONS	741
I.2	CONDITIONAL PROBABILITY	743
I.3	RANDOM VARIABLES	744

I.4	CONDITIONAL DISTRIBUTIONS	745
I.5	FUNCTIONS OF RANDOM VARIABLES	746
I.6	EXPECTATION	747
I.7	CHARACTERISTIC FUNCTIONS	748
I.8	RANDOM SEQUENCES AND RANDOM PROCESSES	751

II	IPA Estimator	755
-----------	----------------------	------------

	Index	761
--	--------------	------------

	About the Authors	771
--	--------------------------	------------