## Contents

Prefac	e xv		2-3	Introduction to Modeling of Thermal and Fluid Systems 47		
СНАР	TED 1			2-3-1 Elementary Heat Transfer Properties		47
				· · · · · · · · · · · · · · · · · · ·		50
Introduction to Control Systems 1			2-4	Linearization of Nonlinear Systems 58		30
1-1 1-2		of Control-System Applications 2 Intelligent Transportation Systems 3 Steering Control of an Automobile 4	2-5	2-4-1 Linearization Using Taylor Series:  Classical Representation 58  Analogies 61	-1 Linearization Classical Repr	
		Steering Control of an Automobile 4	2-6	Project: Introduction to LEGO MINDSTORMS	oject: Introduction to LF	
	1-2-3 1-2-4	Idle-Speed Control of an Automobile 4		NXT Motor—Mechanical Modeling 64	T Motor—Mechanical	
	1-2-4	Sun-Tracking Control of Solar Collectors 5	2-7	Summary 65		
1-3				ences 66	66	
1-3	Open-Loop Control Systems (Nonfeedback Systems) 6			ems 66	66	
1-4	Closed-Loop Control Systems					
1-1	(Feedback Control Systems) 7			PTER 3	3	
1-5		hat Is Feedback, and What Are Its Effects? 8		ion of Differential Equations of Dynamic Systems		
1 5	1-5-1 Effect of Feedback on Overall Gain 9					83
	1-5-2	Effect of Feedback on Stability 9	3-1	Introduction to Differential Equations 84		
	1-5-3	Effect of Feedback on External		3-1-1 Linear Ordinary Differential		
		Disturbance or Noise 10		Equations 85		_
1-6	Types of F	Seedback Control Systems 11	2.2	3-1-2 Nonlinear Differential Equations 85		,
1-7		rsus Nonlinear Control Systems 11	3-2	Laplace Transform 86 3-2-1 Definition of the Laplace Transform		0.0
1-8		ariant versus Time-Varying Systems 12		1		80
1-9		us-Data Control Systems 12		3-2-2 Important Theorems of the Laplace Transform 87	=	
1-10		Oata Control Systems 14		3-2-3 Transfer Function 87		
1-11		y: Intelligent Vehicle Obstacle		3-2-4 Characteristic Equation 89		
		e—LEGO MINDSTORMS 15		3-2-5 Analytic Function 89		
1-12	Summary	23		3-2-6 Poles of a Function 90		
				3-2-7 Zeros of a Function 90		
CHAPTER 2				3-2-8 Complex Conjugate Poles		
Model	ing of Dyna	amic Systems 25		and Zeros 91	•	
2-1	Modeling of Simple Mechanical Systems 26			3-2-9 Final-Value Theorem 93	-9 Final-Value T	
	2-1-1	Translational Motion 26	3-3	Inverse Laplace Transform by Partial-Fraction	erse Laplace Transform	
	2-1-2	Rotational Motion 31		Expansion 93		
	2-1-3	Conversion between Translational and		3-3-1 Partial Fraction Expansion 94	-1 Partial Fraction	
		Rotational Motions 34	3-4	Application of the Laplace Transform to the Solution		.on
	2-1-4	Gear Trains 38		of Linear Ordinary Differential Equations 100	Linear Ordinary Differe	
	2-1-5	Backlash and Dead Zone (Nonlinear		3-4-1 First-Order Prototype System 101	-1 First-Order P	
		Characteristics) 41		3-4-2 Second-Order Prototype System 104	-2 Second-Order	4
2-2	Introduction to Modeling of Simple			3-4-3 Second-Order Prototype System—Fin	:-3 Second-Order	nal
	Electrical Systems 42			Observations 113		
	2-2-1 Modeling of Passive Electrical		3-5	Impulse Response and Transfer Functions		
		Elements 42		of Linear Systems 116		
	2-2-2	Modeling of Electrical Networks 42		3-5-1 Impulse Response 116	-1 Impulse Resp	

## viii Contents

	3-5-2	Time Response Using the Impulse	4-5 4-6	MATLAB		
	2.5.2	Response 118		Summary	211	
	3-5-3	Transfer Function (Single-Input, Single-Output Systems) 119	Refere Proble	ences 212 ems 212		
3-6	Systems of	of First-Order Differential Equations:				
	State Equations 120					
	3-6-1	Definition of State Variables 123			5 16 22-	
	3-6-2 The Output Equation 124		Stability of Linear Control Systems 227			
3-7	Solution of the Linear Homogeneous		5-1	Introduct	ion to Stability 227	
		ation 128	5-2		of Determining Stability 231	
	3-7-1	Transfer Functions	5-3		arwitz Criterion 232	
		(Multivariable Systems) 130		5-3-1	Routh's Tabulation 233	
	3-7-2	Characteristic Equation from		5-3-2	Special Cases When Routh's Tabulation	
	3 , <b>2</b>	State Equations 133			Terminates Prematurely 235	
	3-7-3	State Equations from the Transfer	5-4	MATLAR	3 Tools and Case Studies 238	
	3-7-3	Function 134	5- <del>4</del> 5-5	Summary		
2 0	Casa Stri	dies with MATLAB 137		ences 247	247	
3-8				ems 247		
3-9		ition Revisited—the State-	FIODI	ems 247		
2 10		proach 144				
3-10	Summary	y 149	CHAF	PTER 6		
Refere			Impo	rtant Comp	onents of Feedback	
Proble	ems 150		Control Systems 253			
CHAD	TER 4		6-1	Modeling	of Active Electrical Elements:	
		and Cinnal Flam Comba 163		Operation	nal Amplifiers 254	
RIOCK	Diagrams a	and Signal-Flow Graphs 163		6-1-1	The Ideal Op-Amp 254	
4-1	Block Di	agrams 163		6-1-2	Sums and Differences 256	
	4-1-1	Modeling of Typical Elements of Block		6-1-3	First-Order Op-Amp	
		Diagrams in Control Systems 164			Configurations 256	
	4-1-2	Relation between Mathematical	6-2	Sensors a	nd Encoders in Control Systems 259	
		Equations and Block Diagrams 169		6-2-1	Potentiometer 259	
	4-1-3	Block Diagram Reduction 172		6-2-2	Tachometers 265	
	4-1-4	Block Diagrams of Multi-Input		6-2-3	Incremental Encoder 266	
		Systems: Special Case—Systems with a	6-3	DC Moto	ors in Control Systems 269	
		Disturbance 175		6-3-1	Basic Operational Principles of DC	
	4-1-5	Block Diagrams and Transfer Functions			Motors 270	
		of Multivariable Systems 176		6-3-2	Basic Classifications of PM DC	
4-2	Signal-Fl	low Graphs 178		0 2 2	Motors 270	
	4-2-1	SFG Algebra 180		6-3-3	Surface-Wound DC Motors 271	
	4-2-2	Definitions of SFG Terms 182		6-3-4	Moving-Coil DC Motors 271	
	4-2-3	Gain Formula for SFG 185		6-3-5	Brushless DC Motors 272	
	4-2-4	Application of the Gain Formula		6-3-6	Mathematical Modeling of PM DC	
	4-2-4	between Output Nodes		0-3-0	Motors 273	
		and Noninput Nodes 189		6-3-7	Relation between $K_i$ and $K_b = 276$	
	4-2-5	Simplified Gain Formula 190	6-4		d Position Control of a DC Motor 277	
1 2			0-4	6-4-1		
4-3		agram 192		0-4-1	Speed Response and the Effects of Inductance	
	4-3-1	From Differential Equations to State				
	4.2.2	Diagrams 193			and Disturbance: Open-Loop	
	4-3-2	From State Diagrams to Transfer		( 1 )	Response 278	
		Functions 194		6-4-2	Speed Control of DC Motors:	
	4-3-3	From State Diagrams to State and Output			Closed-Loop Response 280	
		Equations 195		6-4-3	Position Control 282	
4-4	Case Stu	dies 197	6-5	Case Stud	dies: Practical Examples 283	

6.6   1	6-6		Lab: Introduction to LEGO RMS NXT Motor—Modeling and ation 289	7-8	7-7-5  Dominant l	Addition of Poles and Zeros: Introduction to Control of Time Response 368 Poles and Zeros of Transfer Functions 374
6-3-  Seed Response and Mode    7-8-2   The Relative Damping Ratio   376		6-6-1	NXT Motor 289			Summary of Effects of Poles and
6-6-4   Speed Response and Mode   Speed Response and Mode   Speed Response and Mode   Speed Response   Sp					7 0 3	
Net						
5.7   Summary   30		0-0-4			7-0-3	
Problems   300	6.7	Summary				
Problems   300			300	7-9	Case Study:	
The First First First Control Systems   317   1				, ,		
Time   Domain   Performance of Control Systems   317   317   317   317   318   318   318   318   319   3	1100.0.					•
Time Response of Continuous-Data Systems   317   7-9-3   Time Response of a Third-Order   7-9-3   Time Response of Continuous-Data Systems   7-9-3   Not Neglected   383   Not Neglected   383   Not Neglected   384   Not Neglected   385   Not Neglected   385   Not Neglected   386   N	CHAPT	TER 7			7-9-2	
Introduction   318	Time-D	Domain Perfo	ormance of Control Systems 317		7-9-3	
7-2	7-1	-				
Performance of Control Systems 319 The Unit-Step Response and Time-Domain Specifications 321 Trime Response of a Prototype First-Order System 322 Transient Response of a Prototype Second-Order System 326 T-5-1 Damping Ratio and Natural Frequency 327 T-5-2 Maximum Overshoot (0 < √ < 1) 332 T-5-3 Delay Time and Rise Time (0 < √ < 1) 334 T-5-5 Transient Response Performance Trinsient Response Performance Trinsient Response Performance Triteria—Final Remarks 339 T-6-1 Definition of the Steady-State Error 343 T-6-1 Definition of the Steady-State Error 343 T-6-1 Definition of the Steady-State Error 343 T-6-2 Steady-State Error in Systems with a Disturbance 351 Trinsient Response Performance Triteria—Final Remarks 339 T-6-3 Types of Control Systems: Unity-Feedback T-6-5 Steady-State Error Constants 354 T-6-6 Steady-State Error Constants 354 T-6-7 Steady-State Error Constants 354 T-6-7 Steady-State Error Constants 354 T-6-7 Steady-State Error Constants 364 T-7-7 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback T-7-7 Addition of a Zero to the Closed-Loop Transfer Function: 364 T-7-7 Addition of a Zero to the Closed-Loop Transfer Function: 036 T-7-7 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback T-7-7-8 Addition of a Zero to the Closed-Loop Transfer Function: Unity-					7.0.4	
7-10   The Control Labs Introduction to LEGO   Specifications   321   Surprise of a Prototype First-Order   System   322   Surprise of a Prototype Second-Order   System   325   State   Specification   System   326   State   Specification   Specification   System   System   326   State   Specification   System   Sys	7-2					
Specifications   321     MINDSTORMS NXT Motor—Position Control   387				7.10		•
Time Response of a Prototype First-Order System 322  7-5 Transient Response of a Prototype Second-Order System 326  7-5-1 Damping Ratio and Natural Frequency 327  7-5-2 Maximum Overshoot (0 < ζ < 1) 332  7-5-3 Delay Time and Rise Time (0 < ζ < 1) 332  7-5-4 Settling Time (5 and 2 Percent) 336  7-5-5 Transient Response Performance Criteria – Final Remarks 339  7-6 Steady-State Error 343  7-6-1 Definition of the Steady-State Error 343  7-6-2 Steady-State Error in Systems with a Disturbance 351  7-6-3 Types of Control Systems: Unity-Feedback Systems 353  7-6-4 Error Constants 354  7-6-5 Steady-State Error Caused by Nonlinear System Elements 359  7-7 Basic Control Systems and Effects of Adding Poles and Zeros to Transfer Functions 361  7-7-1 Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-8 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-8 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-8 Addition of	7-3			7*10		
System   322   References   393   Problems   394   Problems   395   Problems   394   Problems   410   Pro	7-4			7-11	Summary	393
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		•	* *	Refere	nces 393	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	7-5			Proble	ms 394	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		System 32		CHAP	TERS	
7-5-2 Maximum Overshoot $(0 < \zeta < 1)$ 332 8-1 State-Variable Analysis 411 7-5-3 Delay Time and Rise Time $(0 < \zeta < 1)$ 334 Diagrams, Transfer Functions, and State Diagrams, Transfer Functions, and State Diagrams 412 7-5-4 Settling Time $(5 \text{ and } 2 \text{ Percent})$ 336 8-2-1 Transfer Functions (Multivariable Systems) 412 7-5-5 Transient Response Performance Criteria—Final Remarks 339 8-2-2 Block Diagrams and Transfer Functions of Multivariable Systems 413 7-6-1 Definition of the Steady-State Error 343 8-3 Systems of First-Order Differential Equations: State Equations 415 7-6-2 Steady-State Error in Systems with a Disturbance 351 8-3-1 Definition of State Variables 416 7-6-3 Types of Control Systems: Unity-Feedback Systems 353 8-4 Vector-Matrix Representation of State Equations 417 7-6-4 Error Constants 354 5-2 The Output Equation 417 7-6-5 Steady-State Error Caused by Nonlinear System Elements 359 8-5-1 Significance of the State-Transition Matrix 420 8-5-1 Significance of the State-Transition Matrix 422 8-5-2 Properties of the State-Transition Matrix 422 8-5-2 Properties of the State-Transition Matrix 422 8-5-2 Properties of the State-Transition Matrix 422 8-6-1 State-Transition Equation 423 8-6-1 State-Transition Equation Determined from the State Diagram 426 8-6-1 State-Transition Equations and High-Order Differential Equations and High-Order Differential Equations 429 8-7-7-4 Addition of a Zero to the Closed-Loop Transfer Function: Unity-Feedback Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback Addition of a Zero to the Forward-Path Transfer Functions 430 8-8-8 Relationship between State Equations and Transfer Functions 430 8-9 Characteristic Equations, Eigenvalues,		7-5-1				sis and Controller Design 411
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$						· ·
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$						
7-5-4 Settling Time (5 and 2 Percent) 336 7-5-5 Transient Response Performance Criteria—Final Remarks 339 8-2-1 Multivariable Systems) 412 8-2-2 Block Diagrams and Transfer Functions of Multivariable Systems 413 7-6-1 Definition of the Steady-State Error 343 8-3 Systems of First-Order Differential Equations: State Equations 415 Poisturbance 351 8-3-1 Definition of State Variables 416 8-3-1 Definition of State Variables 416 8-3-2 The Output Equation 417 8-3-3-2 The Output Equation 417 8-3-2 The Output Equation 4		7-5-3		8-2		
7-5-5 Transient Response Performance Criteria—Final Remarks 339  8-2-2 Block Diagrams and Transfer Functions of Multivariable Systems 413  7-6-1 Definition of the Steady-State Error 343  8-3 Systems of First-Order Differential Equations:  7-6-2 Steady-State Error in Systems with a Disturbance 351  7-6-3 Types of Control Systems: Unity-Feedback Systems 353  8-4 Vector-Matrix Representation of State Equations 415  7-6-4 Error Constants 354  7-6-5 Steady-State Error Caused by Nonlinear 8-5 State-Transition Matrix 420  8-3-1 Definition of State Variables 416  7-6-3 Types of Control Systems: Unity-Feedback Systems 353  8-4 Vector-Matrix Representation of State Equations 418  7-6-4 Error Constants 354  7-6-5 Steady-State Error Caused by Nonlinear 8-5 State-Transition Matrix 420  8-5-1 Significance of the State-Transition Matrix 422  7-7-7 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback 8-6 State-Transition Equation 423  8-6-1 State-Transition Equation Determined from the State Diagram 426  7-7-3 Addition of a Zero to the Closed-Loop Fransfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  8-8 Relationship between State Equations 429  Transfer Function: Unity-Feedback 8-8 Relationship between State Equations 429  Transfer Function: Unity-Feedback 8-8 Relationship between State Equations 429  Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		7.5.4			_	
Steady-State Error   343   349   349   340   341   341   342   341   3					8-2-1	
7-6 Steady-State Error 343 7-6-1 Definition of the Steady-State Error 343 8-3 Systems of First-Order Differential Equations: 7-6-2 Steady-State Error in Systems with a Disturbance 351 8-3-1 Definition of State Variables 416 7-6-3 Types of Control Systems: Unity-Feedback Systems 353 8-4 Vector-Matrix Representation 417 7-6-4 Error Constants 354 of State Equations 418 7-6-5 Steady-State Error Caused by Nonlinear 8-5 State-Transition Matrix 420 System Elements 359 8-5-1 Significance of the State-Transition Matrix 422 Poles and Zeros to Transfer Functions 361 8-5-2 Properties of the State-Transition Matrix 422 Transfer Function: Unity-Feedback 8-6 State-Transition Equation 423 Systems 362 8-6-1 State-Transition Equation Determined from the State Diagram 426 Transfer Function 364 8-7 Relationship between State Equations and High-Order Differential Equations 429 Transfer Function 365 8-8 Relationship between State Equations 430 Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		/-3-3			822	
7-6-1 Definition of the Steady-State Error 343 8-3 Systems of First-Order Differential Equations: 7-6-2 Steady-State Error in Systems with a Disturbance 351 8-3-1 Definition of State Variables 416 7-6-3 Types of Control Systems: Unity-Feedback Systems 353 8-4 Vector-Matrix Representation of State Equations 418 7-6-4 Error Constants 354 of State-Transition Matrix 420 System Elements 359 8-5-1 Significance of the State-Transition Matrix 422 Poles and Zeros to Transfer Functions 361 8-5-2 Properties of the State-Transition Matrix 422 Poles and Zeros to Transfer Function: Unity-Feedback Systems 362 8-6-1 State-Transition Equation 423 Systems 362 8-6-1 State-Transition Equation Determined from the State Diagram 426 Transfer Function 364 8-7 Relationship between State Equations and 7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365 8-8 Relationship between State Equations 430 Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,	7-6	Steady-State			0-2-2	
7-6-2 Steady-State Error in Systems with a Disturbance 351 7-6-3 Types of Control Systems: Unity- Feedback Systems 353 8-4 Vector-Matrix Representation 7-6-4 Error Constants 354 7-6-5 Steady-State Error Caused by Nonlinear System Elements 359 8-5-1 Significance of the State-Transition 8-6-1 State-Transition Equation 423 8-6-1 State-Transition Equation Determined 8-6-1 State-Transition Equation Determined 8-6-1 State-Transition Equation Determined 8-7-7-3 Addition of a Pole to the Closed-Loop 8-7-7-4 Addition of a Zero to the Closed-Loop 8-8-8 Relationship between State Equations 8-9 Characteristic Equations, Eigenvalues,	7-0	•		8-3	Systems of	
Disturbance 351  7-6-3 Types of Control Systems: Unity-Feedback Systems 353  7-6-4 Error Constants 354  7-6-5 Steady-State Error Caused by Nonlinear System Elements 359  8-5 State-Transition Matrix 420  System Elements 359  8-5-1 Significance of the State-Transition Matrix 422  Poles and Zeros to Transfer Functions 361  7-7-1 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362  7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback Systems 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback Systems 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback Se-8 Relationship between State Equations and Transfer Functions 429  Transfer Function: Unity-Feedback Se-8 Relationship between State Equations 429  Transfer Function: Unity-Feedback Se-9 Characteristic Equations, Eigenvalues,						
7-6-3 Types of Control Systems: Unity- Feedback Systems 353 8-4 Vector-Matrix Representation 7-6-4 Error Constants 354 of State Equations 418 7-6-5 Steady-State Error Caused by Nonlinear System Elements 359 8-5-1 Significance of the State-Transition 8-5-1 Significance of the State-Transition 8-5-2 Properties of the State-Transition 9-14 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362 8-6-1 State-Transition Equation 423 8-6-1 State-Transition Equation Determined from the State Diagram 426 9-7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364 8-7 Relationship between State Equations and High-Order Differential Equations 429 9-7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-8 Relationship between State Equations and Transfer Functions 430 9-8-8-9 Characteristic Equations, Eigenvalues,						
Feedback Systems 353  7-6-4 Error Constants 354  7-6-5 Steady-State Error Caused by Nonlinear System Elements 359  8-5 State-Transition Matrix 420  System Elements 359  8-5-1 Significance of the State-Transition Matrix 422  Poles and Zeros to Transfer Functions 361  7-7-1 Addition of a Pole to the Forward-Path Systems 362  7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback  7-7-8 Characteristic Equations, Eigenvalues,		7-6-3			8-3-2	The Output Equation 417
7-6-4 Error Constants 354 of State Equations 418 7-6-5 Steady-State Error Caused by Nonlinear System Elements 359 8-5-1 Significance of the State-Transition Matrix 420 8-5-1 Significance of the State-Transition Matrix 422 Poles and Zeros to Transfer Functions 361 8-5-2 Properties of the State-Transition 7-7-1 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362 8-6-1 State-Transition Equation 423 8-6-1 State-Transition Equation Determined from the State Diagram 426 7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364 8-7 Relationship between State Equations and 7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365 8-8 Relationship between State Equations 429 Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,				8-4	Vector-Ma	
System Elements 359  Basic Control Systems and Effects of Adding Poles and Zeros to Transfer Functions 361 7-7-1 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362  7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function 365  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-5-1 Significance of the State-Transition Matrix 422  Properties of the State-Transition Matrix 422  8-5-2 Properties of the State-Transition Matrix 422  8-6-1 State-Transition Equation Determined from the State Diagram 426 High-Order Differential Equations and High-Order Differential Equations High-Order Differential Equations 429 Transfer Function 365  8-8 Relationship between State Equations and Transfer Functions 430 Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		7-6-4			of State Eq	uations 418
7-7 Basic Control Systems and Effects of Adding Poles and Zeros to Transfer Functions 361 7-7-1 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362 7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364 8-6 State-Transition Equation 423 8-6-1 State-Transition Equation Determined from the State Diagram 426 from the State Equations and High-Order Differential Equations 429 Transfer Function 365 8-8 Relationship between State Equations 7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		7-6-5	Steady-State Error Caused by Nonlinear	8-5	State-Trans	
Poles and Zeros to Transfer Functions 361  7-7-1  Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362  7-7-2  Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3  Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4  Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback  8-6  State-Transition Equation 423  8-6-1  State-Transition Equation Determined from the State Diagram 426  Relationship between State Equations and High-Order Differential Equations 429  Relationship between State Equations and Transfer Functions 430  Characteristic Equations, Eigenvalues,			System Elements 359		8-5-1	Significance of the State-Transition
7-7-1 Addition of a Pole to the Forward-Path Transfer Function: Unity-Feedback Systems 362 8-6-1 State-Transition Equation Determined from the State Diagram 426 Transfer Function 364 8-7 Relationship between State Equations and Addition of a Zero to the Closed-Loop Transfer Function 365 8-8 Relationship between State Equations Transfer Function 365 8-8 Relationship between State Equations Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,	7-7	Basic Contr	rol Systems and Effects of Adding			
Transfer Function: Unity-Feedback Systems 362  Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3  Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4  Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback  8-6  State-Transition Equation 423  8-6-1  State-Transition Equation Determined from the State Diagram 426  Relationship between State Equations and High-Order Differential Equations 429  Relationship between State Equations and Transfer Functions 430  Characteristic Equations, Eigenvalues,					8-5-2	-
Systems 362  Addition of a Pole to the Closed-Loop Transfer Function 364  7-7-3  Addition of a Zero to the Closed-Loop Transfer Function 365  7-7-4  Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback  8-6-1  State-Transition Equation Determined from the State Diagram 426  Relationship between State Equations and High-Order Differential Equations 429  Relationship between State Equations and Transfer Functions 430  Characteristic Equations, Eigenvalues,		7-7-1				
7-7-2 Addition of a Pole to the Closed-Loop Transfer Function 364 8-7 Relationship between State Equations and High-Order Differential Equations 429 Transfer Function 365 8-8 Relationship between State Equations 429 Transfer Function 365 7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,				8-6		•
Transfer Function 364 8-7 Relationship between State Equations and Addition of a Zero to the Closed-Loop Transfer Function 365 8-8 Relationship between State Equations 429  7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,					8-6-1	-
7-7-3 Addition of a Zero to the Closed-Loop Transfer Function 365 8-8 Relationship between State Equations 7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		7-7-2		0.7	n ter t	e e
Transfer Function 365 8-8 Relationship between State Equations 7-7-4 Addition of a Zero to the Forward-Path Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		7.7.2		8-7		
7-7-4 Addition of a Zero to the Forward-Path and Transfer Functions 430 Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		1-1-3	•	00		
Transfer Function: Unity-Feedback 8-9 Characteristic Equations, Eigenvalues,		774		0-8		
,		/-/-4		8-0		
			Systems 367	0-2		

	8-9-1 Characteristic Equation from a Differential Equation 433		CHAPTER 9 Root-Locus Analysis 523			
	8-9-2	Characteristic Equation from a Transfer Function 434	9-1	Basic Properties of the Root Loci 524		
	8-9-3	Characteristic Equation from State Equations 434	9-2	Properties o 9-2-1 9-2-2	If the Root Loci 528 $K = 0$ and $K = \pm \infty$ Points 528 Number of Branches on the Root Loci 329	
	8-9-4	Eigenvalues 435		9-2-3	Symmetry of the RL 529	
	8-9-5	Eigenvectors 435		9-2-4	Angles of Asymptotes of the RL:	
	8-9-6	Generalized Eigenvectors 436		, 2 ,	Behavior of the RL at $ s  = \infty$ 531	
8-10	Similarity '	Transformation 438		9-2-5	Intersect of the Asymptotes (Centroid) 532	
	8-10-1	Invariance Properties of the Similarity		9-2-6	Root Loci on the Real Axis 533	
		Transformations 439		9-2-7	Angles of Departure and Angles	
	8-10-2	Characteristic Equations, Eigenvalues,		, , ,	of Arrival of the RL 534	
		and Eigenvectors 439		9-2-8	Intersection of the RL with the	
	8-10-3	Transfer-Function Matrix 439		720	Imaginary Axis 538	
	8-10-4	Controllability Canonical Form 439		9-2-9	Breakaway Points (Saddle Points)	
	8-10-5	Observability Canonical Form 441		J-2-J	on the RL 538	
	8-10-6	Diagonal Canonical Form 443		9-2-10	Angles of Arrival and Departure	
	8-10-7	Jordan Canonical Form 444		<i>J</i> -2-10	of Root Loci at the Breakaway Point 540	
8-11	Decompos	sitions of Transfer Functions 445		9-2-11	Calculation of <i>K</i> on the Root Loci 544	
	8-11-1	Direct Decomposition 446		9-2-12	Summary: Properties of the	
	8-11-2	Direct Decomposition to CCF 447		<i>J-2-12</i>	Root Loci 544	
	8-11-3	Direct Decomposition to OCF 448	9-3	The Root S	ensitivity 549	
	8-11-4	Cascade Decomposition 451	9-4		pects of the Root Loci 553	
	8-11-5	Parallel Decomposition 452	2-4	9-4-1	Effects of Adding Poles and Zeros	
8-12	Controllal	bility of Control Systems 454		7 1 1	to $G(s)H(s)$ 553	
	8-12-1	General Concept of Controllability 455		9-4-2	Addition of Poles to $G(s)H(s)$ 553	
	8-12-2	Definition of State Controllability 456		9-4-3	Addition of Zeros to $G(s)H(s)$ 555	
	8-12-3	Alternate Tests on Controllability 457	9-5		ours: Multiple-Parameter Variation 561	
8-13		ility of Linear Systems 458	9-6	MATLAB '		
0 10	8-13-1	Definition of Observability 459	9-7	Summary		
	8-13-2	Alternate Tests on Observability 459	Refer			
8-14		hip among Controllability,	Probl			
0	Observab	ility, and Transfer Functions 460				
8-15		Theorems on Controllability	CHAPTER 10 Frequency-Domain Analysis 579			
		rvability 462	Frequ	•		
8-16		ly: Magnetic-Ball Suspension	10-1	Introducti	on to Frequency Response 580	
	System			10-1-1	Frequency Response of Closed-Loop	
	8-16-1	The Characteristic Equation 466			Systems 587	
8-17		dback Control 468		10-1-2	Frequency-Domain Specifications 589	
8-18		ement Design through State	10-2		d Bandwidth of the Prototype	
	Feedback			Second-O	rder System 590	
8-19		dback with Integral Control 475		10-2-1	Resonant Peak and Resonant	
8-20	MATLA	3 Tools and Case Studies 481			Frequency 590	
	8-20-1	Description and Use of the State-Space	10.2	10-2-2	Bandwidth 592	
		Analysis Tool 482	10-3	Enects of .	Adding Poles and Zeros to the Path Transfer Function 596	
	8-20-2	Description and Use of tfsym			Effects of Adding a Zero to the	
		for State-Space Applications 485		10-3-1	Forward-Path Transfer Function 596	
8-21	Case Stu	dy: Position Control of the LEGO		10.2.2	Effects of Adding a Pole to the	
0.22		FORMS Robotic Arm System 489		10-3-2	Forward-Path Transfer Function 601	
8-22	Summar		10-4	Numiet C	tability Criterion: Fundamentals 603	
	ences 497		10-4	10-4-1	Stability Problem 603	
Probl	ems 497			TO -T-T		

	10-4-2	Definitions of Encircled	11-2	Design wit	h the PD Controller 668		
		and Enclosed 604		11-2-1	Time-Domain Interpretation		
	10-4-3	Number of Encirclements and			of PD Control 670		
	10.4.4	Enclosures 605		11-2-2	Frequency-Domain Interpretation		
	10-4-4	Principles of the Argument 605		11.2.2	of PD Control 672		
	10-4-5	Nyquist Path 610		11-2-3	Summary of Effects of		
	10-4-6	Nyquist Criterion and the $L(s)$	11.2	Doolan wit	PD Control 674 h the PI Controller 691		
10.5	Name of C	or the $G(s)H(s)$ Plot 611	11-3	11-3-1			
10-5		riterion for Systems with n-Phase Transfer Functions 612		11-3-1	Time-Domain Interpretation and Design of PI Control 693		
	10-5-1			11-3-2	Frequency-Domain Interpretation		
	10-5-1	Application of the Nyquist Criterion to Minimum-Phase Transfer Functions		11-3-2	and Design of PI Control 693		
			11-4	Decian wit	th the PID Controller 707		
10.6	D. L. C 1	That Are Not Strictly Proper 613	11-4		th Phase-Lead and		
10-6		petween the Root Loci and	11-3		Controllers 711		
10.7		st Plot 613		11-5-1	Time-Domain Interpretation		
10-7		e Examples: Nyquist Criterion for		11-3-1	and Design of Phase-Lead Control 713		
		n-Phase Transfer Functions 616		11-5-2	Frequency-Domain Interpretation		
10-8		Adding Poles and Zeros to $L(s)$		11-3-2	and Design of Phase-Lead		
		ape of the Nyquist Plot 621			Control 714		
	10-8-1	Addition of Poles at $s = 0$ 621		11-5-3	Effects of Phase-Lead		
	10-8-2	Addition of Finite Nonzero Poles 623		11-3-3	Compensation 732		
	10-8-3	Addition of Zeros 624		11-5-4	Limitations of Single-Stage Phase-Lead		
10-9		tability: Gain Margin		11-3-4	Control 732		
		e Margin 625		11-5-5	Multistage Phase-Lead Controller 733		
	10-9-1	Gain Margin 626		11-5-6	Sensitivity Considerations 737		
	10-9-2	Gain Margin of Nonminimum-Phase		11-5-7	Time-Domain Interpretation		
		Systems 628		11-3-7	and Design of Phase-Lag		
	10-9-3	Phase Margin 629			Control 738		
10-10	•	Analysis with the Bode Plot 631		11-5-8	Frequency-Domain Interpretation		
	10-10-1	Bode Plots of Systems with Pure		11-3-0	and Design of Phase-Lag		
		Time Delays 634			Control 742		
10-11		tability Related to the Slope of the		11-5-9	Effects and Limitations of Phase-Lag		
	Magnituc	le Curve of the Bode Plot 635		11-3-7	Control 751		
	10-11-1	Conditionally Stable System 636		11-5-10	Design with Lead-Lag		
10-12	Stability 1	Analysis with the		11-3-10	Controller 751		
		le-Phase Plot 638	11-6	Pole-Zero	-Cancellation Design:		
10-13	Constant	-M Loci in the Magnitude-Phase Plane:	11-0	Notch Filt	_		
	The Nich	ols Chart 639		11-6-1	Second-Order Active Filter 756		
10-14	Nichols (	Chart Applied to Nonunity-Feedback		11-6-2	Frequency-Domain Interpretation and		
	Systems	644		11-0-2	Design 757		
10-15	Sensitivit	y Studies in the Frequency	11-7	Forward a	and Feedforward Controllers 765		
	Domain	646	11-8		Robust Control Systems 767		
10-16	MATLA	3 Tools and Case Studies 649	11-9		op Feedback Control 777		
10-17	Summary	7 649	11-7	11-9-1	Rate-Feedback or Tachometer-Feedback		
Referei	nces 649			11-9-1	Control 777		
	ms 650			11-9-2	Minor-Loop Feedback Control with		
				11-9-2	Active Filter 778		
	TER 11		11-10	ΜΑΤΙΔΡ	Tools and Case Studies 781		
Desigr	of Contro	ol Systems 663	11-10	The Conti			
11-1	Introduc	tion 663	Refere		OI Dab 775		
	11-1-1	Design Specifications 663		Problems 794			
	11-1-2 Controller Configurations 665		1 10010	1110 / / 7			
	11-1-3	Fundamental Principles of Design 667	INDEX	( 819			