
Contents

Preface	xi
About the authors	xiii
Control of mechatronic systems software	xv
1 Introduction	1
1.1 Introduction and background	1
1.2 Overall control architecture	3
1.3 Overview of control methods	4
1.4 Software	5
References	6
2 Parameter space based robust control methods	9
2.1 Introduction	9
2.2 Hurwitz stability	10
2.3 $\mathcal{D}$ -stability	19
2.4 Frequency domain control basics	22
2.4.1 Mapping phase margin bounds to parameter space	23
2.4.2 Mapping gain margin bounds to parameter space	26
2.4.3 Mapping sensitivity bounds to parameter space	27
2.5 Case study: automated path following	32
2.6 Case study: Quanser QUBE TM Servo system	35
2.7 Singular frequencies	42
References	44
3 Classical control	47
3.1 Introduction to conventional control	47
3.2 Phase lead compensation	48
3.2.1 Characteristics of phase lead compensators	49
3.2.2 Analytical phase lead compensator design in the frequency domain	50
3.2.3 PD control as a special case of phase lead compensation	56
3.3 Phase lag compensation	60
3.3.1 Characteristics of phase lag compensators	60
3.3.2 Analytical phase lag compensator design in the frequency domain	62
3.3.3 PI control as a special case of phase lag control	65

3.4	Phase lag-lead compensation	72
3.4.1	PID control as a special case of phase lag-lead compensation	74
3.5	Optimisation-based conventional controller design in MATLAB and Simulink	80
3.6	Parameter space based robust conventional controller design	84
3.6.1	Comparison of analytical approach and parameter space phase margin bound computations	84
3.6.2	Case study of parameter space based conventional controller design	85
3.7	Case study: Quanser QUBE™ Servo system	88
3.8	Chapter summary and concluding remarks	89
	References	90
4	Input shaping control	91
4.1	Introduction to input shaping control	91
4.2	Discrete-time NMP zeros	92
4.3	Different feedforward controller designs	94
4.4	Zero phase compensation	95
4.5	Zero phase gain compensation	98
4.6	Characterisation of complex non-minimum phase zeros	99
4.7	Zero phase extended gain compensation	101
4.8	Zero phase optimal gain compensation	103
4.9	Truncated series approximation compensation	108
4.10	Case study: electrohydraulic testing system	108
4.11	Robustness analysis	109
4.12	Chapter summary and concluding remarks	110
	References	110
5	Disturbance observer control	113
5.1	Introduction to disturbance observer control	113
5.2	Continuous-time disturbance observer	113
5.3	Case study: Quanser QUBE™ Servo system	118
5.4	Mapping robust performance frequency domain specifications into disturbance observer parameter space	122
5.5	Case study: SISO disturbance observer control for yaw stability control of a road vehicle	125
5.6	Discrete-time disturbance observer	128
5.7	MIMO decoupling extension of disturbance observer	130
5.8	Case study: MIMO decoupling disturbance observer control for a four-wheel steering vehicle	134
5.9	Case study: MIMO disturbance observer for decoupling the two axes of motion in a piezotube actuator used in an atomic force microscope	139
5.10	Communication disturbance observer	141

5.11 Case study: communication disturbance observer application to vehicle yaw stability control over CAN bus	145
5.12 Chapter summary and concluding remarks	148
References	148
6 Repetitive control	151
6.1 Introduction to repetitive control	151
6.2 Stability analysis of repetitive control system	153
6.2.1 Regeneration spectrum analysis	155
6.2.2 Regeneration spectrum analysis applied to repetitive control	156
6.3 Repetitive controller basics	158
6.3.1 Internal model principle	158
6.3.2 Periodic signal generator	160
6.3.3 Time advance	161
6.3.4 Low-pass filter $q(s)$ and dynamic compensator $b(s)$	162
6.4 Parameter space approach to repetitive control	164
6.4.1 Mapping robust performance frequency domain specifications into controller parameter space	165
6.5 Case study: high-speed atomic force microscope scanner position control	168
6.6 Case study: Quanser QUBE TM Servo system	172
6.7 COMES toolbox: repetitive control system design	174
6.8 Discrete-time repetitive control	174
6.8.1 Basic elements of discrete-time repetitive control	175
6.8.2 Discrete-time repetitive control design procedure based on the parameter space approach	178
6.9 Case study: high-speed atomic force microscope scanner position control	180
6.10 Chapter summary and concluding remarks	184
References	185
7 Summary and conclusions	191
7.1 Summary	191
7.2 Conclusions	192
Appendix A Rapid control prototyping and hardware-in-the-loop simulation	193
Index	195