
Contents

1	Introduction	1
1.1	Motivation of the Book	1
1.2	Issues in Mechanical Systems Control	2
1.3	Robust Motion Control with Perturbation Observer	5
1.4	Robust State Estimation with Perturbation Observer	7
1.5	Coarse/Fine Dual-Stage System	8
1.6	Outline of the Book	10
2	Robust Tracking Control with Hierarchical Perturbation Compensation	11
2.1	Introduction	11
2.2	Tracking controller Design	13
2.2.1	Nominal Model	13
2.2.2	Design of a Sliding Mode Controller	14
2.3	A Class of Perturbation Observers	15
2.4	Three Points of View on the Perturbation Compensation	16
2.4.1	Feedback Perturbation Observer (FBPO)	17
2.4.2	Feedforward Perturbation Observer (FFPO)	18
2.4.3	Sliding Mode Perturbation Observer (SMPO)	18
2.5	Hierarchical Perturbation Compensator (HPC)	19
2.6	Perturbation Compensated Sliding Mode Control	22
2.6.1	A Practical Consideration: Actuator Saturation	25
2.6.2	Simulation	25
2.7	Stability Analysis	27
2.7.1	Boundedness of the Perturbation Compensation Error	28
2.7.2	Effects of the Hierarchical Perturbation Compensation	31
2.8	Experiments	33
2.9	Summary	39

3	Robust Performance of the Multiloop Perturbation Compensator	41
3.1	Introduction	41
3.2	Perturbation Observer Based Robust Controller	42
3.2.1	Notion of Perturbation Observers	42
3.2.2	A Robust Motion Control Structure	44
3.3	A Novel Perturbation Compensation Method	45
3.3.1	Performance Limit	45
3.3.2	Multiloop Perturbation Compensator (MPEC)	45
3.3.3	Performance Tuning of the MPEC	47
3.4	Stability/Performance Analysis	49
3.5	Application to Mechanical Systems	55
3.5.1	Control of Linear XY Table	57
3.5.2	Control of Robot Manipulator	60
3.6	Summary	64
4	Discrete-Time Design and Analysis of Perturbation Observer	65
4.1	Introduction	65
4.2	Discrete Perturbation Observer	67
4.2.1	Perturbation Model	68
4.2.2	A Discrete Perturbation Observer	69
4.2.3	Discrete Q -filter	70
4.3	Perturbation Compensation Error Dynamics	71
4.4	Robustness Analysis	74
4.5	Sensitivity Analysis	75
4.6	Composite Perturbation Observer	80
4.7	Experimental Verification	81
4.8	Summary	84
5	Combined Observer Design for Robust State Estimation and Kalman filtering	87
5.1	Introduction	87
5.2	Combined State Estimator–Perturbation Observer	89
5.2.1	A Combined Observer Synthesis	89
5.2.2	Stability	91
5.2.3	Sensitivity Functions	92
5.3	Application to 2nd Order Mechanical Systems	93
5.3.1	A Design Procedure	93
5.3.2	Sensitivity Analysis	94
5.3.3	Numerical Example	97
5.3.4	Experiment	100
5.4	Robust Kalman Filtering	103
5.4.1	Numerical Example	105
5.5	Summary	108

6	Control of Coarse/Fine Dual-Stage Positioning System	111
6.1	Introduction	111
6.2	Dual-Stage Controller Design	113
6.2.1	Physical Characteristics	113
6.2.2	A Dual-Stage Control Architecture	114
6.2.3	Perturbation Compensator for Robust Tracking Control	115
6.2.4	Null-Motion Controller	117
6.3	Minimum-Time Control with Coarse/Fine Dual-Stage	119
6.3.1	Time-Optimal Trajectory	120
6.3.2	Experimental Example	123
6.4	Application to Micro-Teleoperation	124
6.4.1	Fine Trajectory Tracking	127
6.5	Summary	127
7	Concluding Remarks	129
A	Appendix	133
A.1	Identification of XY Table	133
A.2	Experimental Setup for Micro-Teleoperation	134
A.3	Mathematical Theorems	137
A.3.1	Matrix Inversion Lemma	137
A.3.2	Pontrygin's Minimum Principle	138
	References	139