Contents

1 Introduction 1

2 Introduction to ILC: Concepts, Schematics, and Implementation 7
2.1 ILC for Linear Systems 7
2.1.1 Why ILC? 7
2.1.2 Previous Cycle Learning 8
2.1.3 Current Cycle Learning 10
2.1.4 Previous and Current Cycle Learning 11
2.1.5 Cascade ILC 12
2.1.6 Incremental Cascade ILC 14
2.2 ILC for Non-linear Systems 16
2.2.1 Global Lipschitz Continuity Condition 17
2.2.2 Identical Initialization Condition 19
2.3 Implementation Issues 22
2.3.1 Repetitive Control Tasks 22
2.3.2 Robustness and Filter Design 23
2.3.3 Sampled-data ILC 25
2.4 Conclusion 27

3 Robust Optimal ILC Design for Precision Servo: Application to an XY Table 29
3.1 Introduction 29
3.2 Modelling and Optimal Indices 32
3.2.1 Experimental Setup and Modelling 32
3.2.2 Objective Functions for Sampled-data ILC Servomechanism 33
3.3 Optimal PCL Design 35
3.4 Optimal CCL Design 37
3.5 Optimal PCCL Design 40
3.6 Robust Optimal PCCL Design 42
3.7 Conclusion 44

4 ILC for Precision Servo with Input Non-linearities: Application to a Piezo Actuator 47
4.1 Introduction 47
4.2 ILC with Input Deadzone 50
4.3 ILC with Input Saturation 53
4.4 ILC with Input Backlash 54
4.5 ILC Implementation on Piezoelectric Motor with Input Deadzone 55
4.5.1 PI Control Performance 58
4.5.2 ILC Performance 58
4.6 Conclusion 62

5 ILC for Process Temperature Control: Application to a Water-heating Plant 65
5.1 Introduction 65
5.2 Modelling the Water-heating Plant 67
5.3 Filter-based ILC 72
5.3.1 The Schematic of Filter-based ILC 72
5.3.2 Frequency-domain Convergence Analysis of Filter-based ILC 73
5.4 Temperature Control of the Water-heating Plant 76
5.4.1 Experimental Setup 76
5.4.2 Design of ILC Parameters M and γ 76
5.4.3 Filter-based ILC Results for $\gamma = 0.5$ and $M = 100$ 78
5.4.4 Profile Segmentation with Feedforward Initialization 78
5.4.5 Initial Re-setting Condition 80
5.5 Conclusion 82
5.6 Appendix: The Physical Model of the Water-heating Plant 82

6 ILC with Robust Smith Compensator: Application to a Furnace Reactor 85
6.1 Introduction 85
6.2 System Description 86
6.3 ILC Algorithms with Smith Time-delay Compensator 88
6.4 ILC with Prior Knowledge of the Process 91
6.4.1 ILC with Accurate Transfer Function ($P_0 = \hat{P}_0$) 91
6.4.2 ILC with Known Upper Bound of the Time Delay 94
6.5 Illustrative Examples 95
6.5.1 Simulation Studies 95
6.5.2 Experiment of Temperature Control on a Batch Reactor 97
6.6 Conclusion 98

7 Plug-in ILC Design for Electrical Drives: Application to a PM Synchronous Motor 101
7.1 Introduction 101
7.2 PMSM Model 103

7.3 Analysis of Torque Pulsations 104
7.4 ILC Algorithms for PMSM 106
7.4.1 ILC Controller Implemented in Time Domain 107
7.4.2 ILC Controller Implemented in Frequency Domain 108
7.5 Implementation of Drive System 110
7.6 Experimental Results and Discussions 112
7.6.1 Experimental Results 112
7.6.2 Torque Pulsations Induced by the Load 116
7.7 Conclusion 120

8 ILC for Electrical Drives: Application to a Switched Reluctance Motor 121
8.1 Introduction 121
8.2 Review of Earlier Studies 124
8.3 Cascaded Torque Controller 124
8.3.1 The TSF 125
8.3.2 Proposed Torque to Current Conversion Scheme 126
8.3.3 ILC-based Current Controller 128
8.3.4 Analytical Torque Estimator 130
8.4 Experimental Validation of the Proposed Torque Controller 132
8.5 Conclusion 135

9 Optimal Tuning of PID Controllers Using Iterative Learning Approach 141
9.1 Introduction 141
9.2 Formulation of PID Auto-tuning Problem 144
9.2.1 PID Auto-tuning 144
9.2.2 Performance Requirements and Objective Functions 145
9.2.3 A Second-order Example 145
9.3 Iterative Learning Approach 148
9.3.1 Principal Idea of Iterative Learning 148
9.3.2 Learning Gain Design Based on Gradient Information 150
9.3.3 Iterative Searching Methods 153
9.4 Comparative Studies on Benchmark Examples 154
9.4.1 Comparisons Between Objective Functions 155
9.4.2 Comparisons Between ILT and Existing Iterative Tuning Methods 156
9.4.3 Comparisons Between ILT and Existing Auto-tuning Methods 157
9.4.4 Comparisons Between Search Methods 158
9.4.5 ILT for Sampled-data Systems 160
9.5 Real-time Implementation 161
9.5.1 Experimental Setup and Plant Modelling 161
9.5.2 Application of ILT Method 162
9.5.3 Experimental Results 163

9.6 Conclusion 163
9.7 Appendix 164
9.7.1 Underdamped Case 164
9.7.2 Overdamped Case 165
9.7.3 Critical-damped Case 166

10 Calibration of Micro-robot Inverse Kinematics Using Iterative Learning Approach 169
10.1 Introduction 169
10.2 Basic Idea of Iterative Learning 171
10.3 Formulation of Iterative Identifications 171
10.4 Robustness Analysis with Calibration Error 175
10.5 Example 176
10.5.1 Estimation with Accurate Calibration Sample 177
10.5.2 Estimation with Single Imperfect Factor in Calibration Sample 178
10.5.3 Estimation with Multiple Imperfect Factors in Calibration Sample 179
10.6 Conclusion 180

11 Conclusion 181

References 183

Index 191