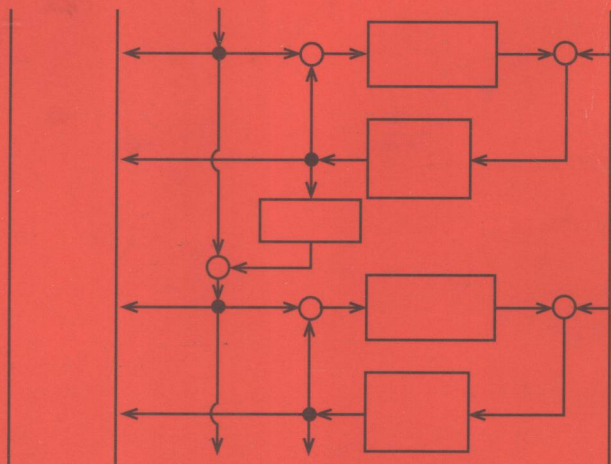


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Yangquan Chen and Changyun Wen

Iterative Learning Control

Convergence, Robustness and Applications



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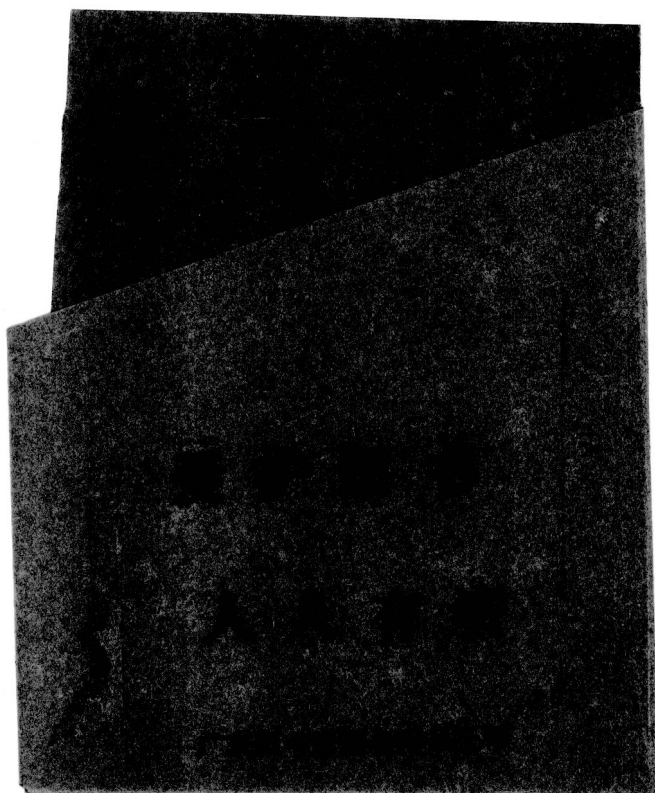
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This work is dedicated to

Our Parents, and

Huifang Dou and Duyun Chen (Jun Jun)

— Yangquan Chen

Xiu Zhou, Wen Wen, Wendy Wen and Qingyun Wen

— Changyun Wen

Preface

A SYSTEM is called a 'repetitive system' when it performs a given task repeatedly. Robotic and functional neuromuscular stimulation systems are examples of such systems. Iterative Learning Control (ILC), which is a relatively new area in the field of control, is proposed to control these types of systems.

Generally speaking, a system under control may have uncertainties in its dynamic model and its environment. One attractive point in ILC is the utilisation of the system repetitiveness to reduce such uncertainties and in turn to improve the control performance by operating the system repeatedly. ILC is a feedforward control strategy that updates, through iterative learning, control signals at every repeated operation. As the number of iterations increases, the system tracking error over the entire operation time period including the transient portion will decrease and eventually vanish. This may not be possible for conventional non-iterative learning control.

This book provides readers with a comprehensive coverage of iterative learning control and emphasises both theoretical and practical aspects. It provides some recent developments in ILC convergence and robustness analysis as well as issues in the ILC design. These include: *High-order Updating Laws, Discrete-time Domain Analysis, Use of the Current Iteration Tracking Error, Initial State Learning, Terminal Iterative Learning Control, ILC Design via Noncausal Filtering or Local Symmetrical Integral (LSI), Iterative Learning Identification* and so on. Several practical applications are included to illustrate the effectiveness of ILC. These applications include: *Rapid Thermal Processing Chemical Vapor Deposition (RTPCVD) Thickness Control in Wafer Fab Industry, Identification of Aerodynamic Drag Coefficient Curve and Trajectory Control in Functional Neuromuscular Stimulation (FNS) Systems*. The application examples provided are particularly useful to readers who wish to capitalise the system repetitiveness to improve system control performance.

The book can be used as a reference or a text for a course at graduate level. It is also suitable for self-study and for industry-oriented courses of continuing education. The knowledge background for this monograph would be some undergraduate and graduate courses including calculus, optimization and nonlinear system control. Some knowledge on optimal control and iteration theory would certainly be helpful. There are 12 chapters in this

monograph. Chapter 1 is to give an introduction of ILC with an extended yet brief literature review. The next eight chapters, i.e. Chapters 2 - 9, provide some new theoretical developments in ILC, followed by two chapters on ILC applications. Conclusions are drawn and some recommendations for future research are given in the last chapter. However, the material in each chapter is largely independent so that the chapters may be used in almost any order desired.

The authors are grateful to Prof. Soh Yeng Chai, Head of the Control and Instrumentation Division, School of Electronic and Electrical Engineering, Nanyang Technological University (NTU), for his advice and encouragement. The first author is deeply thankful to Prof. Jian-Xin Xu and Prof. Tong Heng Lee, Dept. of Electrical Engineering, National University of Singapore (NUS). In addition, the first author would like to thank Mingxuan Sun, Dr. Huifang Dou, Prof. Kok Kiong Tan, Prof. Shigehiko Yamamoto for their collaboration and help. In particular, the first author appreciates Prof. Zenn Z. Bien, Prof. Kevin L. Moore and all the researchers in the ILC Web-link such as Prof. Minh Q. Phan, Prof. Theo J.A. de Vries, Prof. R. W. Longman, Prof. Dr.-Ing. M. Pandit, to name a few, for their constant encouragement during his Ph.D pursue. The authors would like to thank editorial and production staff at Springer-Verlag, especially Alison Jackson, Editorial Assistant (Engineering) and Nicholas Pinfield, Engineering Editor, Springer-Verlag London. Suggestions from Prof. Manfred Thoma, the LNCIS Series Editor, are also appreciated.

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Contents

1. Introduction	1
1.1 Background	1
1.1.1 Repetitive Systems	1
1.1.2 Iterative Learning Control	2
1.1.3 Literature Overview	4
1.2 Objectives	6
1.3 Preview of Chapters	7
2. High-order Iterative Learning Control of Uncertain Nonlinear Systems with State Delays	11
2.1 Introduction	11
2.2 High-order ILC Problem	13
2.3 Convergence Analysis	14
2.4 Simulation Studies	20
2.4.1 Example 1: Effects of Time-delays in State-variables	20
2.4.2 Example 2: Effects of High-order ILC schemes	21
2.4.3 Discussions	24
2.5 Conclusion	25
3. High-order P-type Iterative Learning Controller Using Current Iteration Tracking Error	27
3.1 Introduction	27
3.2 System Description and ILC Updating Law	28
3.3 Convergence Analysis	29
3.4 Simulation Results	33
3.5 Conclusion	34
4. Iterative Learning Control for Uncertain Nonlinear Discrete-time Systems Using Current Iteration Tracking Error	39
4.1 Introduction	39
4.2 Problem Setting and Preliminaries	39
4.3 Main Results and Convergence Analysis	42
4.4 Simulation Illustrations	49
4.5 Conclusion	54

5. Iterative Learning Control for Uncertain Nonlinear Discrete-time Feedback Systems With Saturation	57
5.1 Introduction	57
5.2 Problem Settings	58
5.2.1 Discrete Uncertain Time-varying Nonlinear Systems	58
5.2.2 Discrete-time High-order ILC with a Feedback Controller	58
5.2.3 Assumptions and Preliminaries	61
5.3 Robust Convergence Analysis	63
5.3.1 Robustness Against Bounded Uncertainty and Disturbance	63
5.3.2 Robustness Against Uncertainty or Disturbance Difference	68
5.4 Simulation Illustrations	71
5.5 Conclusion	76
6. Initial State Learning Method for Iterative Learning Control of Uncertain Time-varying Systems	79
6.1 Introduction	79
6.2 Linear Time-varying Uncertain Systems	80
6.3 Nonlinear Time-varying Uncertain Systems	83
6.4 Simulation Illustrations	85
6.5 High-order Initial State Learning	86
6.5.1 High-order Updating Law	86
6.5.2 Convergence Analysis	88
6.5.3 An Illustrative Example	91
6.6 Conclusion	94
7. High-order Terminal Iterative Learning Control with an Application to a Rapid Thermal Process for Chemical Vapor Deposition	95
7.1 Introduction	95
7.2 Terminal Output Tracking by Iterative Learning	96
7.3 RTPCVD Model and Terminal Iterative Learning Control	100
7.4 Simulation Studies	101
7.5 Concluding Remarks	104
8. Designing Iterative Learning Controllers Via Noncausal Filtering	105
8.1 Introduction	105
8.2 Noncausal FIR Filter and Its Properties	106
8.3 Noncausal FIR Filtering Based Iterative Learning Controller	108
8.4 A Convergence Analysis	110
8.5 ILC Design Method	112
8.5.1 Design Method for M	114

8.5.2	Design Method for γ	115
8.5.3	A Limit of ILC Convergence Rate	116
8.5.4	Heuristic Design Schemes	117
8.6	Conclusions	117
9.	Practical Iterative Learning Control Using Weighted Local Symmetrical Double-Integral	119
9.1	Introduction	119
9.2	WLSI ² -type ILC	119
9.2.1	WLSI ² -type ILC Updating Law	120
9.3	Convergence Analysis	123
9.4	ILC Design Method	124
9.4.1	Design Method for T_L	126
9.4.2	Design Method for γ	127
9.4.3	ILC Convergence Rate	127
9.5	Conclusions	128
10.	Iterative Learning Identification with an Application to Aerodynamic Drag Coefficient Curve Extraction Problem	129
10.1	Introduction	129
10.2	A Curve Identification Problem	131
10.3	Iterative Learning Identification	133
10.3.1	Basic Ideas	133
10.3.2	Learning Identification Procedures	133
10.3.3	High-order Iterative Learning Scheme	134
10.4	Convergence Analysis	134
10.5	Learning Parameters Determination	138
10.6	A Bi-linear Scheme	139
10.7	Curve Identification Results From Flight Tests	140
10.8	Conclusion	146
11.	Iterative Learning Control of Functional Neuromuscular Stimulation Systems	147
11.1	Motivations	147
11.2	A Musculoskeletal Model	148
11.3	Simplified First-order Continuous-time ILC Scheme	153
11.4	Simplified Second-order Discrete-time ILC Scheme	153
11.5	Simulation Results and Discussions	154
11.5.1	Fundamental Tests	154
11.5.2	ILC without Feedback Controller	158
11.5.3	ILC Plus a Feedback Controller	161
11.6	Conclusions	162

12. Conclusions and Future Research 177

 12.1 Conclusions 177

 12.2 Future Research Directions 178

References 181

Index 197

1. Introduction

1.1 Background

1.1.1 Repetitive Systems

A 'REPETITIVE SYSTEM' is so called when the system performs a given task repeatedly. This kind of systems, also called the 'multi-pass' processes, was first investigated by J. B. Edwards and D. H. Owens [79, 80]. According to [79, 80], a repetitive dynamic system or multi-pass process is a process possessing the following two novel properties:

- *Repetitive action* in which the process repeats an operation by passing an object or information sequentially through the same dynamic machine or process; and
- *Interaction* between the state or output functions generated during successive operations.

Each individual cycle of operation is termed as a 'pass' or an iteration through the system dynamics. Typical examples of multi-pass processes include automatic ploughing, multi-machine systems such as vehicle conveyers, machining of metals and automatic coal cutting. The early research is to explore the new system characteristics and the main interests are in the stability analysis [79, 183, 207]. The interpretation of multi-pass systems in a framework of the 2-D system theory was found in [30, 204].

It is interesting to note some of the research suggestions from [80]:

- The inter-pass control policy clearly allows some potential for optimizing the behavior of successive batches as the pass number n increases [80, page 279].
- Again, of course, feedforward control based on previous-pass histories must be augmented by present-pass control [80, page 280].

However, there is an important feature behind such kind of system which was not emphasized in [80, 207]. That is, the system repetition can be utilized to improve the system performance by revising the controls from pass to pass. Later in [203, 202, 205, 208, 8, 209], this was realized.