

Studies in Infrastructure and Control

Arun Mozhi Devan Panneer Selvam ·
Fawnizu Azmadi Hussin ·
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Nagarajapandian M.

Optimal Fractional-order Predictive PI Controllers

For Process Control Applications
with Additional Filtering

 Springer

Studies in Infrastructure and Control

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This work is dedicated to:

My favourite Tamil Mozhi, my parents Panneer Selvam and Gomathi, my brother Arul Sivanantham, my sister Anbarasi, my sister-in-law Kavitha and my friends for their endless love, support and encouragement

—P. Arun Mozhi Devan

The love of my life Fazleen, and my hero Faheem, you have been my inspirations, my love will always be with you.

—Fawnizu Azmadi Hussin

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—Kishore Bingi

My parents, wife and friendly colleagues for their unfailing support.

—M. Nagarajapandian

Preface

This book describes the design, development, and implementation of improved PI control techniques using dead-time compensation, structure enhancements, learning functions and fractional ordering parameters. These upgrades will obtain effective set-point tracking abilities with minimal load variations via improved disturbance rejection robust control action. Two fractional-order PI controllers are designed in line with this: fractional-order predictive PI and hybrid iterative learning based fractional-order predictive PI controller, described in the first part of this book. In addition, to minimize the initial load disturbances and stochastic noises, set-point and noise filters are designed by incorporating the essential dynamic parameters of the process models, which are described in Chap. 4. Furthermore, the fractional-order control strategies and filters presented in this book are simulated over first and second-order benchmark process models and further validated using the real-time experimentation of the pilot pressure process plant.

A novel arithmetic-trigonometric optimization algorithm developed is presented in Chap. 5 aims to obtain the effective controller parameters of the proposed techniques. The design uses the essential arithmetic and trigonometric operators to get the optimal parameters even during stochastic disturbances. Furthermore, the optimization technique is simulated with various fields of interest over thirty-three benchmark functions. Also, the proposed method is again validated using the real-time experimentation of the pilot pressure process plant for effective disturbance rejection with robust control actions. In all the performance studies, the proposed controllers, filters, and optimization techniques are compared with the conventional methods to validate the performance improvement.

In this book, these five chapters are structured with a logical sequence of details to provide a better understanding for the readers. A general introduction is presented in Chap. 1. In Chap. 2, a review of the PI controllers and their modifications are presented. Then, a detailed review of these modified PI control techniques such as PPI, FOPI, and ILC-PI controllers are presented. The following section presents the design and development of the proposed fractional-order predictive PI (FOPPI) controller with the help of a dead-time compensating Smith predictor and the robust fractional-order PI (FOPI). The subsequent section discusses the study on

PI controller application in the real-time process plant, followed by selecting benchmark process models. Lastly, the results and discussion of the proposed controller on benchmark process models and the real-time experimentation of the pilot pressure process plant are given.

In the first part of Chap. 3, a review of the PI-based iterative learning controllers, modified structures of the ILC and their modifications are presented. Then, the design of the proposed hybrid iterative learning controller based fractional-order predictive PI (FOPPI) controller based on the current cyclic feedback structure is presented. Lastly, the results and discussion of the proposed controller on benchmark process models and the real-time experimentation of the pilot pressure process plant are given.

Chapter 4 presents the development of the proposed filtering techniques. The first part discusses a review of the various types of filtering techniques in the process control loop. Then, the design of the proposed set-point and noise filters using the essential process dynamics are given. The last part presents the results and discussion of the proposed filters on benchmark process models and the real-time experimentation of the pilot pressure process plant.

Chapter 5 proposes the improvement of the existing sine cosine algorithm (SCA) and arithmetic optimization algorithm (AOA) to form a novel arithmetic-trigonometric optimization algorithm (ATOA) to accelerate the rate of convergence in lesser iterations with mitigation towards getting caught in the same local position. Then the simulation analysis over various benchmark test functions is carried out for validation. In addition, the proposed FOPPI controller will be tuned based on the integral time absolute error (ITAE) value as the desired objective function to find the controller parameters with minimal error while comparing the actual input in the closed-loop system.

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- P. Arun Mozhi Devan, Hussin FA, Ibrahim R, Bingi K, Abdulrab HQ. Fractional-order predictive pi controller for dead-time processes with set-point and noise filtering, *IEEE Access*, 8, 183759–183773, 2020.
- P. Arun Mozhi Devan, Hussin FA, Ibrahim R, Bingi K, Khanday FA. A Survey on the application of WirelessHART for industrial process monitoring and control, *Sensors*, 21(15), 4951, 2021.
- P. Arun Mozhi Devan, Hussin FA, Ibrahim R, Bingi K, Nagarajapandian M, Assaad M. An Arithmetic-Trigonometric Optimization Algorithm with Application for Control of Real-Time Pressure Process Plant, *Sensors*, 22(2), 617, 2022.
- P. Arun Mozhi Devan, Hussin FA, Ibrahim R, Bingi K, Prusty BR. Application of Fractional-Order Signal Filtering Techniques for Dead-Time Process Plants. In *Sustainable Energy and Technological Advancements*, Springer, Singapore, pp. 811–824, 2022.

Contents

1	Introduction	1
1.1	Introduction	1
1.2	Summary	5
	References	5
Part I Fractional-Order Predictive PI Controllers		
2	Fractional-Order Predictive PI Controller for Dead-Time Process Plants	11
2.1	PID Controller and Its Modifications	11
2.2	Related Works on Modified PI Control Strategies	12
2.2.1	Predictive PI Controller	13
2.2.2	Fractional-Order PI Controller	15
2.3	Related Works on Control of Pressure Process Plant	17
2.4	Development of Proposed Fractional-Order Predictive PI Controller	18
2.4.1	Fractional-Order PI Controller	18
2.4.2	Fractional-Order Predictive PI Controller	19
2.4.3	Stability Analysis	22
2.5	Selection of Benchmark Process Models	23
2.6	Case Studies on Real-Time Pressure Process Plant	26
2.6.1	Piping and Instrumentation Diagram of Pressure Process Plant	26
2.6.2	Schematics of Experimental Setup	26
2.6.3	Implementation of Proposed Fractional-Order Controllers and Filters	29
2.6.4	Performance Measure	30
2.7	Simulation Study on Benchmark Process Models	30
2.7.1	First-Order System	31
2.7.2	Second-Order System	33

- 2.8 Experimental Analysis on Real-Time Pilot Pressure Process Plant 36
 - 2.8.1 Mathematical Modelling of Pressure Process Plant 36
 - 2.8.2 Experimental Results 38
- 2.9 Summary 40
- References 41
- 3 Hybrid Iterative Learning Controller-Based Fractional-Order Predictive PI Controller 47**
 - 3.1 PI-Type Iterative Learning Control 47
 - 3.2 Development of Proposed Hybrid Iterative Learning Controller-Based Fractional-Order Predictive PI Controller 48
 - 3.2.1 Iterative Learning Controller 48
 - 3.2.2 Learning Function and Q-Filter Design 49
 - 3.2.3 Hybrid Iterative Learning Controller-Based Fractional-Order Predictive PI Controller 52
 - 3.3 Simulation Study on Benchmark Process Models 52
 - 3.3.1 First-Order System 53
 - 3.3.2 Second-Order System 56
 - 3.4 Real-Time Pilot Pressure Process Plant Experimentation 60
 - 3.5 Summary 63
 - References 64
- Part II Filtering and Optimization Techniques**
- 4 Fractional-Order Filtering Techniques 69**
 - 4.1 Related Works on Filtering in Process Control Loop 69
 - 4.1.1 Set-Point Filter 69
 - 4.1.2 Noise Filter 70
 - 4.2 Development of Proposed Fractional-Order Filtering Techniques 72
 - 4.2.1 Fractional-Order Set-Point Filter 72
 - 4.2.2 Fractional-Order Noise Filter 73
 - 4.3 Simulation Study on Benchmark Process Models 75
 - 4.3.1 Performance of Fractional-Order Set-Point Filter 75
 - 4.3.2 Performance of Fractional-Order Noise Filter 79
 - 4.3.3 Performance of Combined Fractional-Order Set-Point and Noise Filters 82
 - 4.4 Real-Time Pilot Pressure Process Plant Experimentation 87
 - 4.4.1 Performance of Proposed Set-Point Filter 88
 - 4.4.2 Performance of Proposed Noise Filter 90
 - 4.4.3 Performance of Combined Set-Point and Noise Filters 93
 - 4.5 Summary 95
 - References 96

- 5 Arithmetic-Trigonometric Optimization Algorithm** 99
 - 5.1 Related Works on Optimization Algorithms 99
 - 5.1.1 Sine Cosine Optimization Algorithm 99
 - 5.1.2 Arithmetic Optimization Algorithm 101
 - 5.2 Development of the Proposed Arithmetic-Trigonometric Optimization Algorithm 102
 - 5.2.1 Sine Cosine Algorithm 103
 - 5.2.2 Arithmetic Optimization Algorithm 104
 - 5.2.3 Arithmetic-Trigonometric Optimization Algorithm 108
 - 5.2.4 Pseudocode of Arithmetic-Trigonometric Optimization Algorithm 110
 - 5.2.5 Tuning of Controller Parameters Using Arithmetic-Trigonometric Optimization Algorithm 112
 - 5.3 Performance of the Proposed Arithmetic-Trigonometric Optimization Algorithm 113
 - 5.3.1 Benchmark Functions 114
 - 5.3.2 Numerical Analysis on Benchmark Functions 114
 - 5.3.3 Convergence Analysis of Benchmark Functions 126
 - 5.3.4 Experimental Analysis of Real-Time Pressure Process Plant for Optimized Fractional Predictive PI Controller 128
 - 5.4 Summary 130
 - References 130

- Appendix A: Design of Fractional-Order PI and Predictive PI Controllers** 135

- Appendix B: Brief on SCA and AOA Algorithms** 139

- Index** 145

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Acronyms

AI	Analogue Input
AO	Analogue Output
AOA	Arithmetic Optimization Algorithm
APAOA	Adaptive Parallel Arithmetic Optimization Algorithm
ARX	Auto Regressive eXogenous
ATOA	Arithmetic-Trigonometric Optimization Algorithm
CRONE	Commande Robuste d'Ordre Non Entier
DTC	Dead-Time Compensator
FOC	Fractional-Order Controller
FOMCON	Fractional-Order Modelling and Control
FOPDT	First-Order Plus Dead Time
FOPI	Fractional-Order PI
FOPPI	Fractional-Order Predictive PI
FOTF	Fractional-Order Transfer Function
FPI	Fuzzy PI
FPPI	Filtered Predictive PI
AGGPC	Generalized Predictive Controller
HV	Hand Valve
ILC	Iterative Learning Control
ILCFOPPI	Iterative Learning Control Fractional-order Predictive PI
ITAE	Integral Time Absolute Error
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LOF	Lower Order Filter
MATLAB	Matrix Laboratory
MIMO	Multi Input Multi Output
MOA	Math Optimizer Accelerated
MOP	Math Optimizer Probability
MPC	Model Predictive Control
MPCPI	Model Predictive Control PI
MRAC	Model Reference Adaptive Control
NPI	Non-linear PI