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Tamal Roy
Ranjit Kumar Barai

Robust Control-Oriented Linear Fractional Transform Modelling

Applications for the μ-Synthesis Based H∞ Control

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Preface

The interest in model-based control has been growing due to the developments of new techniques for the design of advanced control law and availability of tools for mathematical modelling of complex systems. However, the design approach of some particular control laws demands a specific form of mathematical modelling. The popular μ-synthesis-based H_∞ controller design necessitates a particular form of model known as the linear fractional transformation (LFT) model. Although lot of literature was available at various sources, a comprehensive text that elaborates the general theoretical techniques to derive the LFT model of complex systems in a systematic manner was absent. The authors felt the need for a comprehensive text during their research on application of robust control in complex systems like robots and mechatronic systems.

This book covers a new paradigm of system modelling—the robust control-oriented linear fractional transformation (LFT) modelling. A dynamic system expressed in LFT modelling framework paves the way for the application of modern robust controller design techniques like μ-synthesis method for H_∞ controller design. This book covers the generalized robust control-oriented LFT modelling representation of the MIMO system depending upon the uncertainty structure, system dynamics, and the dimensions of the input–output. The modelling framework results in a compact and manageable representation of uncertainty modelling in the form of feedback-like structure that is suitable for design and implementation of the robust control technique like μ-synthesis-based H_∞ control theory. This book also describes the application of the proposed methodology in a variety of advanced mechatronic systems like the laboratory-scale helicopters and wheeled mobile robots with and without slip.

We hope that the contents of the book would be useful for teaching and research. Any suggestions for further improvements to the book are most welcome. We are grateful to all who encouraged and helped us directly or indirectly during the preparation of the manuscript.

Kolkata, India
August 2022

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Dr. Tamal Roy received his Bachelor's degree in Electrical Engineering from the West Bengal University of Technology, Kolkata, 2005. He received his Master in Mechatronics Engineering from the National Institute of Technical Teachers Training and Research, Kolkata in 2008 and completed his Ph.D. from Jadavpur University in 2016. In 2008, he joined the Department of Electrical Engineering at Hooghly Engineering and Technology College as a Lecturer. Since 2011, he has been working as an Assistant Professor in the Electrical Engineering Department of MCKV Institute of Engineering and presently is working as Head of the Department. His current research interests include Adaptive Control, Uncertainty Modelling, System Identification and Robust Control of Non-linear systems.

Dr. Ranjit Kumar Barai graduated in Bachelor of Electrical Engineering in 1993 and Master of Electrical Engineering in 1995 from Jadavpur University, India, and Ph.D. in Artificial Systems Science (with specialization in Mechatronics and Robotics) in 2007 from Chiba University, Japan. He has performed Post-Doctoral research at Rolls-Royce Corporate Laboratory at Nanyang Technological University, Singapore, in 2015-16 on robotized manufacturing. He is now Professor in the Control Systems Division, Department of Electrical Engineering, Jadavpur University. He has more than 20 years of working experience in industry, research and teaching at graduate and post-graduate levels. His research interests include Mechatronics, Robotics, Control Systems, Machine Learning and Soft-computing, Modelling and System Identification, and Real-time systems.

Chapter 1
Introduction

1.1 Motivation

This book aims to deliberate a systematic approach of mathematical modelling of complex physical system that would enable the control system engineer to effectively design H_∞ robust controller with guaranteed performance. It is a well-known fact that the design approach of some particular control law demands specific mathematical model. For example, classical SISO control requires transfer function model, state feedback control requires state-space model, back-stepping control requires strict feedback form, fuzzy logic control requires fuzzy logic model, adaptive control requires linear parametric model and so on. The popular μ-synthesis-based H_∞ control requires linear fractional transformation (LFT) [1] model of the given plant to utilize the available design tools.

From the modelling point of view, this book introduces a modelling technique to achieve optimum control performance by including the control objective in the system modelling. Instead of attempting to apply general mathematical modelling technique, which is quite often complicated, control-oriented modelling of the real-world system results into a compact and practicable representation of the mathematical modelling. In fact, control-oriented system modelling and identification [2] is a convenient modelling approach that leads to a useful representation of the physical system with an ultimate objective of control system design for it.

The performance of the robust controller largely depends on the uncertainty representation of the system. A systematic way for the uncertainty modelling of the dynamic systems in the closed-loop structure is in the form of LFT modelling by the norm bounded unstructured, dynamic perturbation matrix. The book deals with control-oriented LFT modelling of complex dynamic systems with the aim to utilize the LFT model for μ-synthesis-based H_∞ [2] control law design. The H_∞ control law design employing μ-synthesis technique has been a popular control system design

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paradigm for the last decade. However, widespread application of this μ-synthesis-based H_∞ control law design for arbitrarily complex systems was afflicted by lack of any systematic derivation of LFT model of such systems. The contents presented in this text will largely fill this gap.

1.2 Organization of This Book

A step-by-step systematic approach has been adopted in this book to elaborate the concept and applications of the main theme of this book. The important and notable aspects related to general modelling techniques are elaborated at first. Then the origin and representation of model uncertainty have been explained. Then the method of casting the uncertainty in the LFT framework has been elaborated. A generalized approach of control-oriented LFT modelling has also been presented. Finally, several applications of control-oriented LFT modelling and subsequent H_∞ control law design employing μ-synthesis based on the derived LFT models have been elaborated.

Chapter 2 covers a comprehensive survey on the mathematical modelling of real physical systems.

Chapter 3 presents a theoretical discussion for H_∞ control-oriented LFT modelling of nonlinear multivariable systems.

Chapter 4 covers a comprehensive survey on the μ-synthesis-based H_∞ controller design technique. This chapter extensively discussed two major aspects of the H_∞ controller, mainly optimal and sub-optimal control techniques. Finally, the H_∞ control law is implemented by using μ-synthesis to obtain optimal control performance.

Chapter 5 deals with the generalized control-oriented LFT modelling of a nonlinear MIMO system with an equal number of input–output combinations in the first approach. In the second approach, a generalized representation of the proposed modelling for the nonlinear MIMO system for any number of input–output combinations is derived by considering the system parameters varying within certain intervals. The state matrix representation in the functional form for the parametric model is used to realize the uncertain parameters. Finally, the uncertain parameters of the system are expressed as affine functions to derive the generalized control-oriented LFT modelling for a nonlinear MIMO system.

Chapter 6 presents application of the concepts of the previous chapters to derive robust control-oriented LFT modelling for the 2DOF spring-mass-damper system by considering all possible parametric uncertainties and external disturbance signals. Finally, H_∞ control law is implemented to validate the effectiveness of the derived modelling byμ-analysis-based robust stability and performance analysis. The transient response of the system during time domain analysis exhibits excellent performance both in the normal and in the presence of external noise signals.

Chapter 7 covers robust control-oriented LFT modelling approach for the laboratory-scale helicopter for further design of the H_∞ controller by μ-synthesis.

The linearized mathematical modelling has been formulated for the twin rotor MIMO system considering all its cross-coupled dynamics to recast the system modelling in terms of uncertainty representation by truly integrating the control objectives.

Chapter 8 mainly discussed a systematic approach towards the control-oriented LFT modelling of a nonlinear multivariable mobile robotic system, i.e. wheeled mobile robot (WMR). The LFT modelling of the wheeled mobile robot is derived for the H_∞ controller to achieve robust stability and performance even in the presence of all possible uncertainties.

Chapter 9 addressed the improved modelling quality of the WMR by introducing the longitudinal slip dynamics into the robust control-oriented LFT modelling structure.

References

1. Doyle, J., Glover, K., Zhou, K.: Robust and Optimal Control. Prentice Hall (1996)
2. Chen, J., Gu, G.: Control-Oriented System Identification: An H_∞ Approach. Wiley (2000)

Chapter 2
Mathematical Modelling of Real Physical Systems

2.1 Introduction

Mathematical model depicts functional correspondence between the input variables and output variables of a real physical system. These mathematical functions may be linear or nonlinear and may contain a room for uncertainty depending upon the complexity of the real physical system. Modelling uncertainty may arise due to the limited knowledge about the actual physical phenomena involved in the system and associated laws of nature during the manifestation of the dynamic behaviour of the system. Many physical phenomena may be involved simultaneously in one single system. For example, even a simple system like electric motor involves electrical principles, magnetic principles, principles of mechanics, thermal effects, etc. More accurate model may involve the principles of tribology, principles of vibration, earth's magnetic and capacitive influence and so on. More the physical laws are involved to describe the dynamics of the physical system, more complex will be the structure of the model and the number of the parameters and variables required to describe the model will be large. Even after a thorough investigation of the involvement of natural phenomena with a system, at a certain stage, we will have to halt due to the limitation of understanding of the nature at that moment. Thus uncertainty is bound to exist in any mathematical model of a real physical system.

Thus, control system engineer faces a big challenge to find out the mathematical model appropriate for analysis and synthesis of the control system for a physical system. He can overcome this challenge by application of his engineering skill and engineering common sense to estimate the level of complexity needed in the mathematical model to meet the requirements and objectives of the analysis and synthesis of the control system satisfactorily. This decision making is very important before any modelling task is undertaken.

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