Adaptive Control of Systems with Actuator Failures

Springer-Verlag London Ltd.

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With 50 Figures

Springer

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British Library Cataloguing in Publication Data
Adaptive control of systems with actuator failures
1. Adaptive control systems. 2. Actuators 3. Fault-tolerant computing
I. Tao, Gang
629.8′36
ISBN 978-1-84996-917-8 ISBN 978-1-4471-3758-0 (eBook)
DOI 10.1007/978-1-4471-3758-0
A catalog record for this book is available from the Library of Congress.

ISBN 978-1-84996-917-8

springeronline.com

Originally published by Springer-Verlag London Berlin Heidelberg in 2004

Typesetting: Electronic text files prepared by authors
69/3830-543210 Printed on acid-free paper SPIN 10945681

Preface

Actuator failures in control systems may cause severe system performance deterioration and even lead to catastrophic closed-loop system instability. For example, many aircraft accidents were caused by operational failures in the control surfaces, such as rudder and elevator. For system safety and reliability, such actuator failures must be appropriately accommodated. Actuator failure compensation is an important and challenging problem for control systems research with both theoretical and practical significance.

Despite substantial progress in the area of actuator failure compensation, there are still many important open problems, in particular those involving system uncertainties. The main difficulty is that the actuator failures are uncertain in nature. Very often it is impossible to predict in advance *which* actuators may fail during system operation, *when* the actuator failures occur, *what* type and *what* values of the actuator failures are. It may also be impractical to determine such actuator failure parameters after a failure occurs. It is appealing to develop control schemes that can accommodate actuator failures without explicit knowledge of the occurrences of actuator failures and the actuator failure values. Adaptive control, which is capable of accommodating system parametric, structural, and environmental uncertainties, is a suitable choice for such actuator failure compensation schemes.

This book presents our recent research results in designing and analyzing adaptive control schemes for systems with unknown actuator failures and unknown parameters. The main feature of the adaptive actuator failure compensation approach developed in this book is that no explicit fault detection and diagnosis procedure is used for failure compensation. An adaptive law automatically adjusts the controller parameters based on system response errors, so that the remaining functional actuators can be used to accommodate the actuator failures and systems parameter uncertainties.

The book is in a comprehensive and self-contained presentation, while the developed theory is in a general framework readily applicable to specific practical adaptive actuator failure compensation problems. The book can be used as a technical reference for graduate students, researchers, and engineers from fields of engineering, computer science, applied mathematics, and others who have a background in linear systems and feedback control at the undergraduate level. It can also be studied by interested undergraduate students for their thesis projects.

This book is focused on adaptive compensation of actuator failures characterized by the failure model that some unknown control inputs may get stuck at some unknown fixed (or varying) values at unknown time instants and cannot be influenced by the control signals. The type of fixed-value actuator failures, referred to as "lock-in-place" actuator failures, is an important type of actuator failures and is often encountered in many critical control systems. For example, in aircraft flight control systems, the control surfaces may be locked in some fixed places and hence lead to catastrophic accidents. Varying value failures can occur, for example, due to hydraulics failures that can produce unintended movements in the control surfaces of an aircraft.

For actuator failure compensation, a certain redundancy of actuators is needed. For a system with multiple actuators, one case is that all actuators have the same physical characteristics; for example, they are segments of a multiple-segment rudder or elevator for an aircraft. For this case, a reasonable (natural) design for the applied control inputs is one with equal or proportional actuation for each actuator, that is, all control inputs are designed to be equal or proportional to each other. This actuation scheme is employed throughout the book, except for Chapter 5, where a multivariable design is used for the case when the actuators are divided into several groups and each group has actuators of the same physical characteristics (for example, an aircraft has a group of four engines and a group of three rudder segments), and within each group, an equal or proportional actuation is used.

With 12 chapters, the book systematically develops adaptive state tracking and output tracking control schemes for systems with parameter and actuator failure uncertainties. Designs and analysis for both linear systems and nonlinear systems with unknown actuator failures are covered. Key issues for adaptive actuator failure compensation, namely, design condition, controller structure, error equations, adaptive laws for updating the controller parameters, analysis of stability and tracking properties, are given in detail. Extensive simulation results are presented to verify the desired closed-loop system performance. This work is aimed at developing a theoretical framework for adaptive control of systems with actuator failures, to provide guidelines for designing control systems with guaranteed stability and tracking performance in the presence of system parameter uncertainties and failure uncertainties.

Chapter 1 presents some background material. Basic concepts and fundamental principles of adaptive control systems are introduced. The actuator failure compensation problems for linear systems and nonlinear systems are formulated. An overview of several existing actuator failure compensation design methods, including multiple models, switching and tuning designs, fault diagnosis designs, adaptive designs, and robust designs, is also given.

Chapters 2–8 address the adaptive actuator failure compensation problems for linear time-invariant systems with unknown actuator failures. Chapter 2 presents several model reference state feedback state tracking designs. For a linear time-invariant system with m actuators, the adaptive actuator failure compensation problem for up to $m-1$ unknown actuator failures is investigated. Designs for three types of actuator failures: "lock-in-place," parametrizable time-varying, and unparametrizable time-varying, are developed. Conditions and controller structures for achieving plant-model state matching, adaptive laws for updating the controller parameters, and analysis of closed-loop stability and asymptotic state tracking properties are addressed in a unified and comprehensive framework. State feedback actuator failure compensation designs for a class of multi-input systems are also derived. A more general case of up to $m-q$ ($q \geq 1$) unknown actuator failures is then addressed. Necessary and sufficient conditions for actuator failure compensation are derived. It is shown that the number of fully functional actuators is crucial in determining the actuation range that specifies the compensation design conditions in terms of system actuation structures. Such conditions are required for both a nominal design using system and failure knowledge and an adaptive design without such knowledge. An adaptive actuator failure compensation control scheme based on such system actuation conditions is developed for systems with unknown dynamics parameters and unknown "lock-in-place" actuator failures. Simulation results are presented to verify the desired system performance with failure compensation.

Chapter 3 investigates the state feedback output tracking problem for single-output linear time-invariant systems with any up to $m-1$ uncertain failures of the total m actuators. In particular, adaptive rejection of the effect of certain unmatched input disturbances on the output of a linear time-invariant system is addressed in detail. A lemma that presents a novel basic property of linear time-invariant systems is derived to characterize system conditions for plant-model output matching. An adaptive disturbance rejection control scheme is developed for such systems with uncertain dynamics parameters and disturbances. This adaptive control technique is applicable to control of systems with actuator failures whose failure values, failure time instants, and failure patterns are unknown. A solution capable of accommodating the "lock-in-place" and time-varying actuator failures in the presence of any up to $m-1$ uncertain failures of the total m actuators is presented to this adaptive actuator failure compensation problem. The developed adaptive actuator failure compensation schemes ensure closed-loop stability and asymptotic output tracking despite the uncertainties in actuator failures and system parameters. Simulation results verify the desired system performance in the presence of unknown actuator failures.

Chapter 4 develops a model reference adaptive control scheme using output feedback for output tracking for linear time-invariant systems with unknown actuator failures. An effective output feedback controller structure is proposed for actuator failure compensation. When implemented with true matching parameters, the controller achieves desired plant-model output matching, and when implemented with adaptive parameter estimates, the controller achieves closed-loop stability and asymptotic output tracking, which is also verified by simulation results. Compensation of varying failures is achieved based on an output matching condition for a system with multiple inputs whose actuation vectors may be linearly independent.

Chapter 5 deals with the output tracking problem for multi-output linear time-invariant systems using output feedback. Two adaptive control schemes based on model reference adaptive control are developed for a class of multi-input multi-output systems with unknown actuator failures. An effective controller structure is proposed to achieve the desired plant-model output matching when implemented with matching parameters. Based on design conditions on the controlled plant, which are also needed for nominal plant-model output matching for a chosen controller structure, two adaptive controllers are proposed and stable adaptive laws are derived for updating the controller parameters when system and failure parameters are unknown. All closed-loop signals are bounded and the system outputs track some given reference outputs asymptotically, despite the uncertainties in failures and system parameters. Simulation results are presented to demonstrate the performance of the adaptive control system in the presence of unknown rudder and aileron failures in an aircraft lateral dynamic model.

Chapter 6 studies adaptive pole placement control for linear time-invariant systems with unknown actuator failures, applicable to both minimum and nonminimum phase systems. A detailed analysis shows the existence of a nominal controller (when both system and actuator failure parameters are known) that achieves the desired pole placement, output tracking, and closed-loop signal boundedness. For that case when both system and failure parameters are unknown, an adaptive control scheme is developed. A simulation study with a linearized lateral dynamic model of the DC-8 aircraft is presented to verify the desired actuator failure compensation performance.

Chapter 7 applies several adaptive control schemes developed in the previous chapters to a linearized longitudinal dynamic model of a transport aircraft model. The tested adaptive schemes include state feedback design for state tracking, state feedback design for output tracking, and output feedback design for output tracking. Various actuator failures are considered. Extensive simulation results for different cases are presented to demonstrate the effectiveness of the adaptive actuator failure compensation designs.

Chapter 8 presents a robust adaptive control approach using output feedback for output tracking for discrete-time linear time-invariant systems with uncertain failures of redundant actuators in the presence of the unmodeled dynamics and bounded output disturbance. Technical issues such as plant-model output matching, adaptive controller structure, adaptive parameter update laws, stability and tracking analysis, and robustness of system performance are solved for the discrete-time adaptive actuator failure compensation problem. A case study is conducted for adaptive compensation of rudder servomechanism failures of a discrete-time Boeing 747 dynamic model, verifying the desired adaptive system performance.

Chapters 9–11 deal with actuator failure compensation problems for nonlinear systems. Chapter 9 formulates such problems and develops adaptive control schemes for feedback linearizable systems. Different structure conditions that characterize different classes of systems amenable to actuator failure compensation are specified, with which adaptive state feedback control schemes are developed for systems with uncertain actuator failures.

Chapter 10 addresses actuator failure compensation problems for nonlinear systems that can be transformed into parametric-strict-feedback form with zero dynamics. Two main cases are studied for adaptive actuator failure compensation: systems with stable zero dynamics, and systems with extra controls for stabilization. Design conditions on systems admissible for actuator failure compensation are clarified. Adaptive state feedback control schemes are developed, which ensure asymptotic output tracking and closed-loop signal boundedness despite the uncertainties in actuator failures as well as in system parameters. An adaptive control scheme is applied to a twin otter aircraft longitudinal nonlinear dynamics model in the presence of unknown failures in a two-segment elevator servomechanism. Simulation results verify the desired adaptive actuator failure compensation performance.

Chapter 11 presents an adaptive control scheme that achieves stability and output tracking for output-feedback nonlinear systems with unknown actuator failures. A state observer is designed for estimating the unavailable system states, based on a chosen control strategy, in the presence of actuator failures with unknown failure values, time instants, and pattern. An adaptive controller is developed by employing a backstepping technique, for which parameter update laws are derived to ensure asymptotic output tracking and closed-loop signal boundedness, as shown by detailed stability analysis. An extension of the developed adaptive actuator failure compensation scheme to nonlinear systems whose dynamics are state-dependent is also given to accommodate a larger class of nonlinear systems. An application to controlling the angle of attack of a nonlinear aircraft model in the presence of elevator segment failures is studied, with simulation results presented to illustrate the effectiveness of the failure compensation design.

Chapter 12 presents concluding remarks and suggests a list of theoretical and practical topics for further research in this area of adaptive control.

To help the readers understand the basic designs of adaptive control in the absence of actuator failures, the book includes an appendix that presents the schemes of model reference adaptive control using state feedback for state tracking, state feedback for output tracking, output feedback for output tracking, and multivariable design, as well as adaptive pole placement control. Key issues such as *a priori* system knowledge, controller structure, plant-model matching, adaptive laws, and stability are addressed.

This book describes adaptive actuator failure compensation approaches for effectively controlling uncertain dynamic systems with uncertain actuator failures. It addresses the theoretical issues of actuator failure models, controller structures, design conditions, adaptive laws, and stability analysis, with extensive simulation results on various aircraft system models. Design guidelines provided here may be used to develop advanced adaptive control techniques for control systems with controller adaptation and failure compensation capacities to improve reliability, maintainability, and survivability. The research leading to this book was supported by the National Aeronautics and Space Administration (NASA). However, the views and contents of this book are solely those of the authors and not of NASA.

Acknowledgements

We would like to express our thanks to Professors Karl Åström, Petros Ioannou, Petar Kokotović, Frank Lewis, and Kumpati Narendra for their knowledge and encouragement, to Dr. Jovan Boskovic for his inspiring work, to Professor Marios Polycapou for his help, to Professor Jack Stankovic for his interest and support, to Professors Michael Demetriou and Hong Wang for their comments, to Dr. Xiao-Li Ma for her contribution to Chapter 2, to Mr. Juntao Fei for his contribution to Chapter 8, to Mr. Richard Hueschen for his useful discussion about transport aircraft dynamics and actuator configurations, to Drs. Emin Faruk Kececi and Avinash Taware for their discussion, to Professors Zong-Li Lin and Steve Wilson for their support, and to the anonymous reviewers for their comments, which all have been continually motivating and highly beneficial to our related research, whose results have been reported in this book.

The first three authors wish to gratefully acknowledge the support by the NASA Langley Research Center to this work.

We are especially grateful to our families for their love and their support to our research work, which made this project possible.

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