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Fault Tolerant Control Schemes Using Integral Sliding Modes

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We dedicate this book to
Mirza's parents, wife Attiya Tariq and
children Mehreen, Abdur Rafe and Mohib
Chris' parents
Halim's wife Nor Mazuita Noor Azizuddin
and son Aydin Yusuf.

Preface

Control is an essential part of many new technology developments, from cell phones to passenger aircraft and from washing machines to oil refineries. The objective of many control applications is to maintain the output (of the process) in the face of unknown disturbances, whilst in others, it is tracking a reference signal and minimising the tracking error, which is important. Ensuring the closed-loop stability of the overall system in the presence of unknown disturbances and in the face of uncertainties which arise as a result of creating an approximate mathematical model used for the controller design is an important part of the control design process. In addition, issues of operating safety, reliability and availability of the system, especially in safety critical plants like aircraft and nuclear reactors, are of great importance. Safety critical systems like aircraft became the basis for the initial research in the field of fault tolerant control systems. Faults or failures in these safety critical systems cannot be totally avoided, however their effects (in terms of human mortality and economic loss) can be mitigated using fault tolerant control schemes. Fault Tolerant Control (FTC) schemes are an important aspect in safety critical systems and seek to maintain overall system stability and acceptable performance in the face of faults and failures within the system. One way to achieve high level of availability is to ensure a suitable level of redundancy in terms of the key actuators and sensors within the system. In emergency situations, this redundancy can be manipulated in a way to achieve fault tolerance. Therefore, increasing demands for safety, reliability and high system performance have motivated the need for fault tolerant control and has stimulated research in this area. For the design of fault tolerant controllers, many different design paradigms have been proposed in the literature. This book will focus on one particular methodology—the so-called integral sliding modes. The objective is to show how the robustness properties of sliding mode control—especially integral sliding modes—can be used within the framework of FTC to provide an increase in the survivability, reliability and stability of safety critical systems.

The book is a mix of theoretical developments and case studies relating to aerospace systems and is organised as follows:

In Chap. 1, the definitions and basic terminologies of FTC and some typical types of faults at the sensor, actuator and component level are defined. In addition, the difference between fault and failure is clearly explained. Different types of fault/failure models used in the literature to design fault tolerant schemes against the actuator faults/failures and component faults are discussed. An introduction to FTC is given together with an introduction to different fault tolerant control methods used in the literature based on passive and active approaches. The terminologies used in the fault detection and isolation framework are defined, and some of the techniques which can be used for FDI are also documented.

In Chap. 2, the concept, properties and design principles of sliding mode control are explained. Different methods which can be used to implement sliding mode controllers in real and practical applications are also given. The concept of integral sliding modes is defined next, with an explanation of how it differs from the classical sliding mode control approach explained earlier in the chapter. A detailed procedure for the design of integral sliding mode control laws together with a special choice of sliding surface which helps to mitigate the effects of unmatched uncertainty is explained. Finally, some motivation for the use of integral sliding modes as a candidate for FTC is discussed.

In Chap. 3, an integral sliding mode FTC scheme is presented, which considers the combination of integral sliding modes and a Control Allocation scheme. The concept of a virtual control is also explained, which is then used by the Control Allocation scheme to achieve the demanded actuator position. The FTC scheme described in this chapter uses the estimated actuator effectiveness level to distribute the control effort among the actuators without changing the underlying ISM controller. A rigorous closed-loop stability analysis is carried out and it is proved that the scheme can handle some level of error in estimating the actuator effectiveness. Furthermore, in order to compute the controller parameters such that the closed-loop stability condition (given in the chapter) is satisfied, an LMI synthesis procedure is described. The resulting fault-tolerant Control Allocation scheme can cope with actuator faults and certain total actuator failures without degrading the desired performance. A benchmark model of a large civil aircraft is used to validate the feasibility of the scheme.

In Chap. 4, a passive FTC scheme is described where the combination of integral sliding mode control with fixed control allocation is considered. The FTC scheme has the capability to deal with actuator faults/failures without any FDI scheme and is suitable for the case where fault information is not available to the controller. A detailed LMI-based procedure is provided to synthesise the controller parameters and a rigorous closed-loop stability analysis is carried out in the presence of unmatched uncertainty for a suitable set of actuator faults/failures.

Chapter 5 focuses on an output feedback integral sliding mode control allocation scheme within the framework of FTC. This chapter relaxes the assumption made in the previous chapters that full state information is available for the controller design. The chapter also builds on the idea that information about actuator faults/failures is not available to the controller. A direct control allocation scheme is employed in this case to distribute the control signal among the actuators. In order to estimate the plant states, an unknown input observer (UIO) is employed and the necessary conditions for the existence of the UIO are included. A rigorous closed-loop stability analysis is carried out and a stability condition is posed in an LMI framework through which the controller and observer gains are computed. A benchmark model of a large civil aircraft is used to demonstrate the efficacy of the scheme by considering component faults, together with faults or failures in the actuator channels.

In Chap. 6, an integral sliding mode augmentation scheme is considered in order to introduce fault tolerance at an actuator level. The scheme is based on an *a posteri* approach, building on an existing state feedback controller designed using only the primary actuators, without the need to remove or alter existing control loops. The control allocation scheme is developed based on the idea that if the primary actuators are healthy, the secondary actuators should not be activated, and the secondary actuators should only be activated for fault tolerant purposes if the primary actuators are faulty. This FTC approach depends on information about the actuator effectiveness levels, to distribute the control signals among the available actuators in the set. Possible errors in estimating the actuator effectiveness by the FDI scheme are taken into consideration while a closed-loop stability condition is described, which must be satisfied to ensure stability in the case of faults or failures. The efficacy of the scheme is tested by applying it to a nonlinear benchmark model of a large civil aircraft.

In Chap. 7, a nonlinear fault tolerant scheme for the control of longitudinal motion of an aircraft is considered and an integral sliding mode control allocation scheme is combined with a backstepping structure. In fault-free conditions, the closed-loop system is governed by the backstepping controller and the integral sliding mode control allocation scheme only influences the performance if faults/failures occur in the primary control surfaces. In this situation, the allocation scheme redistributes the control signals to the secondary control surfaces and the scheme is able to tolerate total failures in the primary actuator. A backstepping scheme taken from the existing literature is designed for flight path angle tracking (based on the nonlinear equations of motion) and this is used as the underlying baseline controller in nominal conditions.

In Chap. 8, the ideas of integral sliding mode control allocation discussed in Chap. 3 are extended for Linear Parameter Varying (LPV) plants. For the design of the virtual control law, the parameter varying input distribution matrix is factorised into a fixed matrix and a matrix with varying components. In this chapter, a control law is developed which is automatically scheduled with respect to the varying plant operating conditions in order to ensure closed-loop stability for a wider range of operating conditions. The scheme also depends on information about actuator effectiveness levels for control signal distribution. An effective LMI synthesis procedure is described to compute the parameters of the controller and a rigorous closed-loop stability analysis is undertaken, which ensures that certain classes of faults or failures can be dealt with over the entire operating envelope (with the assumption that the redundancy is available in the system). A benchmark LPV model of the large civil aircraft is used to demonstrate the efficacy of the FTC scheme.

In Chap. 9, the integral sliding mode FTC scheme for LPV plants described in Chap. 8 is implemented in real-time on the SIMONA motion flight simulator at the Delft University of Technology, The Netherlands.

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[1] The European Flight Mechanics Action Group FM-AG(16) on Fault Tolerant Control was established in 2004 and concluded in 2008. It represented a collaboration involving thirteen European partners from industry, universities and research establishments under the Group for Aeronautical Research and Technology in Europe (GARTEUR) program.

The authors would like to thank all those who kindly gave their approval to use the pictures and illustrations in this book. The illustrations remain the property of the copyright holders.

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Acronyms

Nomenclature

$\emptyset$	Empty set
α, β, γ	Angle of attack, sideslip and flight path angle (rad)
$\mathbb{C}$	Field of complex numbers
$\det(\cdot)$	Determinant of a matrix
$\mathbb{E}(\cdot)$	Mathematical expectation
$\mathbb{R}$	Field of real numbers
$\mathscr{R}(\cdot)$	Range space of a matrix
$\subset$	Subset
$\mathrm{diag}\ (\cdot)$	Diagonal matrix
$\mathrm{rank}\ (\cdot)$	Rank of a matrix
σ	Switching function
$\mathscr{S}$	Sliding surface
$\Vert . \Vert$	Euclidean norm (vectors), induced spectral norm (matrices)
ν	Virtual control input
p, q, r	Roll rate, pitch rate and yaw rate (deg/s)
s	Laplace variable
$\mathrm{trace}\ (\cdot)$	Trace of a square matrix
$\mathrm{Var}\ (\cdot)$	Variance
V_{tas}	True airspeed (m/s)
$\mathscr{W}$	Allowable set of fault or failure
W	Actuator effectiveness matrix
ϕ, θ, ψ	Roll angle, pitch angle and yaw angle (rad)
$\lambda_{min(.)}, \lambda_{max}(.)$	Minimum and maximum eigenvalues
h_e, x_e, y_e	Geometric earth position with respect to the z (altitude), x and y axis (m)

Abbreviations

AFTC	Active Fault Tolerant Control
BRL	Bounded Real Lemma
CA	Control Allocation
CG	Centre of Gravity
DI	Dynamic Inversion
DOF	Degree of Freedom
EPR	Engine Pressure Ratio
FDI	Fault Detection and Isolation
FPA	Flight Path Angle
FTC	Fault Tolerant Control
FTLAB	Flight Lab
GARTEUR	Group for Aeronautical Research and Technology in Europe
GS	Gain Scheduling
ISM	Integral Sliding Modes
ISMC	Integral Sliding Mode Control
IMM	Interacting Multiple Model
LMI	Linear Matrix Inequality
LPV	Linear Parameter Varying
LQR	Linear Quadratic Regulator
LTI	Linear Time Invariant
MMST	Multiple Model Switching and Tuning
MPC	Model Predictive Control
MRAC	Model Reference Adaptive Control
PFTC	Passive Fault Tolerant Control
PIM	Pseudo-Inverse Method
RECOVER	REconfigurable COntrol for Vehicle Emergency Return
SIMONA	SImulation, MOtion and NAvigation
SMC	Sliding Mode Control
STC	Self Tuning Control
UIO	Unknown Input Observer
VSC	Variable Structure Control
VSCS	Variable Structure Control Systems
ail, aol	Inboard and Outboard Left Aileron
air, aor	Inboard and Outboard Right Aileron
s.p.d.	Symmetric Positive Definite
sp	Spoiler