Advances in Industrial Control

Halim Alwi
Christopher Edwards
Chee Pin Tan

Fault Detection and Fault-Tolerant Control Using Sliding Modes

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(*continued after Index*)

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We dedicate this book to

Halim's wife Nor Mazuita Noor Azizuddin,
Chris' parents: with love and gratitude,
Chee Pin's wife Priscilla, and children Joseph & Joy-Anne.

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies..., new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

In this *Advances in Industrial Control* monograph the authors, Halim Alwi, Christopher Edwards and Chee Pin Tan, remark that "In the last five decades, control system methodologies have evolved... into sophisticated and advanced electronic devices for controlling high performance and highly unstable systems... Some of these control methodologies... have found success in industry with a wide range of applications. Other control methodologies have not so readily been accepted by industry." One such technique that has not been so readily accepted is "sliding mode control" and it is this method that is at the heart of this new monograph. In fact, looking back over the *Advances in Industrial Control* monograph series (a series of over a hundred volumes from the series inception in 1991), we were surprised to find that this is the *very first* monograph on the sliding mode control method in the series!

In many ways, this monograph demonstrates the true theoretical and applications depth to which the sliding mode control paradigm has been developed today. It has three very strong themes: *control design, theoretical extensions* and *industrial applications*. For sliding mode *control*, Chap. 3 carefully builds up the reader's understanding of the design method. This is presented in structured steps using a number of simulation examples, which can easily be replicated and experienced by the reader. The phenomenon of "chattering" is exhibited and how easy it is to overcome is demonstrated. Of the extensions, there are many; however, there are two themes here. One theme is the development of technical tools like a sliding mode observer and its properties (Chaps. 4 and 5). The second theme is the use of sliding mode control in fault-tolerant control (FTC) and fault detection and isolation (FDI). There is an excellent overview of the FTC and FDI issues in Chap. 2 and then a number of Chaps. 6, 7, 8, 9, and 10 follow up these issues.

The third strong theme in the monograph is the application of the authors' schemes to computer simulations, test rigs and ultimately, an advanced flight simulator. The primary application area pursued in the monograph is the control of large passenger and cargo aircraft under extreme safety-critical conditions. These aircraft control problems supply a theme that is threaded through the monograph as it progresses. Most impressive are the two chapters at the end of the monograph describing a sliding mode control allocation scheme (Chap. 11) developed for testing on a high-fidelity 6 DOF research flight simulator, SIMONA (SImulation MOtion NAvigation) based at Delft University of Technology, The Netherlands, and a subsequent set of simulated recreations (Chap. 12) of the accident that occurred to the ELAL Flight 1862 known as the Bijlmereer Incident in which a cargo aircraft suffered the catastrophic loss of two engines from the same wing along with additional wing damage. The objective of the simulations was to demonstrate the potential of the new sliding mode control algorithm to assist in this type of situation. These simulation tests included trials using experienced pilots to obtain an independent assessment of the capabilities of the algorithm. This sort of research demonstrates industrial control engineering at its very best.

Other examples and demonstrations in the monograph include VTOL aircraft computer simulations, a laboratory-scale crane system and a d.c. motor system; all examples that give the monograph a real connection to problems of industrial control engineering.

As a first monograph on the methods of sliding mode control in the *Advances in Industrial Control* series, this is a very substantial and impressive contribution. Its mixture of the theoretical and the practical should appeal to a wide range of readers, from both the academic and industrial control engineering communities. The Editors are very pleased to have this monograph enter the series as it well demonstrates and offers the real prospects of advances in industrial control using a potentially undervalued control technique, that of the sliding mode method.

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Preface

In safety critical systems, there is an inherent requirement that, overall, some level of possibly degraded performance must be maintained even in the event of serious faults or failures occurring within the system. The ability to deal with situations in which faults and failures occur, was originally termed ‘self repairing control’. However, it is now more commonly referred to by the moniker ‘fault tolerant control’. The aerospace industry has often been the driver and focus of such research. As recent crashes in London and in Madrid demonstrate, malfunctions, however statistically unlikely, still occur in civil aviation contexts, and the prevention of significant loss of life depends almost solely on the correct judgement and skill of the pilot. Generally speaking fault tolerant control (FTC) schemes are classified as either passive or active. Passive schemes operate independently of any fault information and basically exploit the robustness of the underlying control paradigm. Such schemes are usually less complex, but are conservative, in order to cope with ‘worst case’ fault effects. Active fault tolerant controllers react to the occurrence of faults, typically by using information from a fault detection and isolation (FDI) scheme, and they invoke some form of reconfiguration. This represents a more flexible architecture. Early publications focussed on so-called projection methods whereby, if a particular fault was detected and identified, a corresponding control law from a pre-specified and pre-computed set of controllers was selected and switched online. Subsequent methods have tended to focus on online adaptation or online controller synthesis. Reconfiguration is usually necessary in the event of severe faults such as total failures in actuators/sensors. For example, if a sensor or actuator fails totally, no adaptation within that feedback loop can recover performance without modification to the choice of actuators and sensors coupled via the controller (i.e., reconfiguration). Fault tolerant control may be considered to be at the intersection of a number of research fields, and is essentially an open problem. Unsurprisingly many robust control paradigms have been used as the basis for fault tolerant controllers. The possibilities of exploiting the inherent robustness properties of sliding modes for fault tolerance have previously been explored for aerospace applications and the work in [128] argued that sliding mode control has the potential to become an alternative to reconfigurable control.

Observer-based methods are the most popular form of model-based fault detection filter. Typically (in linear observer schemes) the output estimation error formed as the difference between the measured plant output and the output of the observer, is scaled to form a residual. During fault-free operation, this residual should be 'zero' but should become 'large' and act as an alarm in the presence of a fault. A strand of work pioneered by the authors has been the development of sliding mode observers for fault estimation. This is achieved by appropriate scaling and filtering of the so-called 'equivalent output error injection', which represents the average value the nonlinear output error injection term has to take to maintain a sliding motion. This is a unique property of sliding mode observers and emanates from the fact that the introduction of a sliding motion forces the outputs of the observer to exactly track the plant measurements. Even in the presence of actuator faults, the sliding mode forces the outputs of the observer to perfectly track the measurements, and accurate estimation of the states is still possible. The fault reconstruction signal is not computed from a residual calculation based on the output estimation error (which will be zero during the sliding motion), but from the equivalent output error injection signal. Consequently accurate state estimation and fault estimation can be, in principle, achieved simultaneously from a single (sliding mode) observer. This is quite different to the situation in the case of traditional linear observer designs for FDI which require a trade-off between robustness with respect to the state estimation, and fault sensitivity for detection using output error based residuals. Robust state estimation, whilst retaining fault sensitivity, is a property unique to sliding mode observers.

The book will cover the theoretical development and implementation of sliding mode schemes for fault tolerant control. A key development in this book considers sliding mode control allocation schemes for fault tolerant control based on integral action and a model reference framework. Unlike many control allocation schemes in the literature, one of the main contributions described in this book is the use of actuator effectiveness levels to redistribute the control signals to the remaining healthy actuators when faults/failures occur. A rigorous stability analysis and design procedure is developed from a theoretical perspective for this scheme. A fixed control allocation structure is also rigorously analyzed in the situation when information on actuator effectiveness levels is not available. The proposed scheme shows that faults and even certain total actuator failures can be handled directly without reconfiguring the controller. The later chapters of the book present the results obtained from real-time hardware implementations of the controllers on the 6-DOF SIMONA flight simulator at Delft University as part of the GARTEUR AG16 programme.

Chapter 1 gives an overview of the recent developments in the area of fault detection and fault tolerance control. It is intended to provide motivation for the theoretical developments which follow in the subsequent chapters.

Chapter 2 begins with the definition of the terms fault and failure and briefly discusses the different types of faults and failures which can occur in actuators and sensors—with specific aircraft examples. The chapter introduces the concept of fault tolerant control and gives a general overview of the different FTC and FDI research fields. The main concepts and strategies behind some of the FTC and FDI schemes in the literature, as well as their advantages and drawbacks, are also discussed.

Chapter 3 gives a brief introduction to the concept of sliding mode control and examines its properties. This chapter also highlights the benefits of sliding modes when applied to the fields of FTC and FDI. A simple pendulum example is used to introduce the concept. The unit-vector approach for multi–input systems, sliding surface design and tracking requirements (integral action and model reference based tracking) are also discussed. Chapter 3 ends with some discussions on the benefits and motivation for sliding mode control in the fields of FTC and FDI.

Chapter 4 considers sliding modes applied to the problem of observer design. A historical development is outlined leading to the description of a specific class of sliding mode observer which will be used throughout the book. It will be shown how the unique properties associated with the so-called equivalent injection signal necessary to maintain sliding can be exploited to reconstruct actuator and sensor faults modelled as additive perturbations to the inputs and the outputs of the plant. Design methodologies based on Linear Matrix Inequalities (LMIs) are presented. These approaches exploit all the available degrees of freedom associated with the choice of the observer gains. The chapter describes sliding mode observers which can reconstruct faults and yet be robust to disturbances/uncertainties which may corrupt the quality of the reconstructions resulting from mismatches between the model about which the observer is designed and the real system. Initially, the design method is formulated for the case of actuator faults. A comparison is also made between the sliding mode observer schemes developed in the chapter and more traditional linear unknown input observers which are prevalent in the literature.

Chapter 5 examines the assumptions that must be made for the observer schemes described in Chap. 4 to be applicable. (These amount to relative degree one minimum phase limitations on the transfer function matrices relating the unknown fault signals to the measurements.) This chapter explores ways of obviating these limitations, at the expense of creating cascaded observer structures. The components of the cascade will be observer formulations taken from Chap. 4, and explicit constructive algorithms will be given to ensure the overall scheme can still accurately estimate actuator faults in the case where the relative degree between the faults and the measurements is greater than or equal to two. The advantages these schemes offer over traditional linear methods (particularly UIOs) will be demonstrated.

Chapter 6 will focus specifically on sensor faults. Different formulations will be considered in which the measured output signals are filtered to yield 'fictitious systems' in which sensor faults appear as 'actuator faults'. Consequently, the actuator fault reconstruction ideas from the previous chapters can then be applied to the fictitious system to reconstruct the sensor fault. The results will also be extended to the case of unstable plants which result in nonminimum phase configurations post-filtering.

Chapter 7 considers the real-time implementation of the sensor fault reconstruction schemes (for FDI and FTC) from Chap. 6 on a laboratory crane and a small DC motor rig. These rigs provide cheap, safe and practical demonstrators for the ideas presented in Chap. 6. The data collection and (subsequent) controller implementation has been achieved using MATLAB® and dSPACE®. Estimates of the sensor faults, obtained from online sliding mode FDI schemes have been used to correct the measured outputs from the sensors. The 'virtual sensors' have been used in the control algorithm to form the output tracking error signal which is processed to generate the fault tolerant control signal.

Chapter 8 presents a new sliding mode scheme for reconfigurable control. The controller is based on a state-feedback scheme where the nonlinear unit-vector term is allowed to adaptively increase when the onset of a fault is detected. The scheme is applied to a benchmark aircraft problem. In comparison to other fault tolerant controllers which have been previously implemented on this model, the controllers proposed in this book are simple and yet are shown to work across the entire 'up and away' flight envelope. Excellent rejection of a certain class of actuator faults is shown. However, the proposed controller cannot directly cope with the total failure of an actuator. In the second half of the chapter, the use of sensor fault reconstruction methods to correct faulty measurements prior to the control law calculations, hence effecting fault tolerant control, is demonstrated. Here, a formal closed-loop analysis is made of the resulting schemes. An example of such a method applied to a benchmark aircraft problem is described.

Chapter 9 proposes an online sliding mode control allocation scheme for fault tolerant control. The effectiveness level of the actuators is used by the control allocation scheme to redistribute the control signals to the remaining actuators when a fault or failure occurs. The chapter provides an analysis of the sliding mode control allocation scheme and determines the nonlinear gain required to maintain sliding. The allocation scheme shows that faults and even certain total actuator failures can be handled directly without reconfiguring the controller.

Chapter 10 describes an adaptive model reference sliding mode fault tolerant control scheme with online control allocation. As in Chap. 9, the control allocation scheme uses the effectiveness level of the actuators to redistribute the control signals to the remaining actuators when a fault or failure occurs. Meanwhile, the adaptive nonlinear gain and reference model provide online tuning for the controller. This chapter provides a rigorous stability analysis for the model reference scheme. The scheme has been tested on a linearisation of the ADMIRE aircraft model to convey the ideas associated with the proposed scheme and shows that various faults and even total actuator failures can be handled.

Chapter 11 describes the implementation of the sliding mode allocation schemes from Chap. 9 on the 6-DOF research flight simulator SIMONA at Delft University of Technology, the Netherlands. The controller from Chap. 9 is implemented in 'C' and runs on the 'flight control' computer associated with SIMONA. Real-time implementation issues are discussed and a range of fault scenarios from the GARTEUR AG16 benchmark are tested and discussed.

Chapter 12 presents the ELAL flight 1862 (Bijlmermeer incident) scenario—which is one of the case studies of GARTEUR AG16. The results presented in this chapter demonstrate the outcome of the 'flight testing' campaign and the GARTEUR AG16 final workshop at Delft University of Technology in November 2007. The results represent the successful real-time implementation of a sliding mode controller on SIMONA with experienced test pilots flying and evaluating the controller.

Finally, Chap. 13 makes some concluding remarks and offers suggestions for future work.

Leicester, UK — Halim Alwi
Leicester, UK — Christopher Edwards
Bandar Sunway, Malaysia — Chee Pin Tan

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In addition to the hardware platform used to test the controllers, the underlying benchmark aircraft model, which was used as a basis for the simulator, has been the result of many man-hours of development by different contributors over the years—most recently Hafid Smaili and Jan Breeman of NLR (National Aerospace Laboratory), The Netherlands and Dr. Andres Marcos, formally at the University of Minnesota, USA and now at Deimos Space, Madrid, Spain. Other contributors to the development of the benchmark model include Coen van der Linden and Dr. Thomas Lombaerts (Delft University of Technology), Prof. Gary Balas (University of Minnesota), David Breeds (QinetiQ) and Stuart Runham (DSTL). We would like to thank all those who were involved in the GARTEUR FM-AG16 action group on fault tolerant control. Their support and contributions to the discussions in the AG16 program are highly appreciated.

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.

[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 auspices of the Group for Aeronautical Research and Technology in Europe (GARTEUR) program.

The provision of two grants from the Engineering and Physical Sciences Research Council (EPSRC), which funded most of the work which is described in this book, is also gratefully acknowledged.

Contents

List of Notations

Acronyms

air, ail	inboard right and inboard left ailerons
aor, aol	outboard right and outboard left ailerons
cmd	command signal
ru, rl	upper and lower rudders
sp	spoiler
6-DOF	6 Degree of Freedom
ATC	Air Traffic Controller (airport control tower)
CA	Control Allocation
CFIT	Controlled Flight Into Terrain
CG	Centre of Gravity
DFDR	Digital Flight Data Recorder
DI	Dynamic Inversion
DME	Distance Measuring Equipment
EPR	Engine Pressure Ratio
FBW	Fly-By-Wire
FDI	Fault Detection and Isolation
FPA	Flight Path Angle
FTC	Fault Tolerant Control
GARTEUR	Group for Aeronautical Research and Technology in Europe
GS	Glide Slope
IAS	Indicated Airspeed
ILS	Instrument Landing System
IMM	Interactive Multiple Model
KIAS	Indicated Air Speed in Knots
KLM	Royal Dutch Airlines
LMI	Linear Matrix Inequality
LOC	Localizer Capture
LPV	Linear Parameter Varying
LTI/LTV	Linear Time Invariant/Varying
MAC	Mean Aerodynamic Chord

MCT	Maximum Continuous Thrust
MMST	Multiple Model Switching and Tuning
MPC	Model Predictive Control
MRAC	Model-reference Adaptive Control
NLR	National Aerospace Laboratory, the Netherlands
PIM	Pseudo-Inverse Method
ROV	Remote Operating Vehicle
SIMONA	SImulation, MOtion and NAvigation (flight simulator)
SMC	Sliding Mode Control
s.p.d.	symmetric positive definite
TAS	True Airspeed
VOR	VHF Omni-directional Radio Range

Mathematical notation

p, q, r	roll, pitch and yaw rate (rad/s)
V_{tas}	true air speed (m/s)
α, β	angle of attack and sideslip angle (rad)
ϕ, θ, ψ	roll, pitch and yaw angle (rad)
h_e, x_e, y_e	geometric earth position along the z, x and y axis (m)
$\|\cdot\|$	Euclidean norm or induced spectral norm
$\lambda(\cdot)$	eigenvalues
$\bar{\lambda}(\cdot), \underline{\lambda}(\cdot)$	largest and smallest eigenvalues
Γ	integral action design matrix
$\nu(t)$	virtual control input and pseudo control
A^{T}	transpose of matrix A
$\mathbb{C}$	field of complex numbers
$\mathbb{C}_{-}$	the set of strictly negative complex numbers
D, E	robust sliding mode observer gain
F, G	feedback and feedforward control matrix
$G(\mathrm{s})$	transfer function
G_l, G_n	sliding mode observer gain matrices
J	cost function
K	actuator fault/failure distribution matrix
$\mathcal{K}$	sliding mode design matrix
L	sliding mode observer design matrix
L_x	sliding mode control design matrix
M	actuator fault distribution matrix (observer)
N	sensor fault distribution matrix
$\mathcal{N}(A)$	null space of the matrix A
Q	uncertainty distribution matrix
$\mathbf{Q}, \mathbf{R}$	LQR/LMI weighting matrix
$\mathcal{R}$	rectangle
$\mathbb{R}$	field of real numbers
$\mathbb{R}_{+}$	the set of strictly positive real numbers
$\mathrm{Re}(\cdot)$	real part of a complex number
s	sliding mode switching function

$\mathtt{s}$	Laplace variable
$\mathrm{sgn}(\cdot)$	signum function
S	sliding mode matrix
$\mathcal{S}$	sliding surface
V	Lyapunov function
$\mathcal{V}_r$	truncated ellipsoid
$\mathbf{V}$, $\mathbf{W}$	weighting matrix
W	actuator effectiveness distribution matrix
$\mathcal{W}$	allowable fault set
X	LMI variable

Chapter 1
Introduction

In the last five decades, control system methodologies have evolved from simple mechanical feedback structures into sophisticated and advanced electronic devices for controlling high performance and highly unstable systems which optimise cost and control effort. Some of these control methodologies, for example the 'three term' PID (Proportion, Integral and Derivative) controller [12] and the Kalman filter [237, 268], have found success in industry with a wide range of applications. Other sophisticated control methodologies have not so readily been accepted by industry.

Some of the strategies that have received a good deal of attention in the last couple of decades are multivariable robust and adaptive control methods (see for example [175, 216, 228, 297]). This is motivated by the need to optimise the performance of safety critical systems such as aircraft, chemical plants and nuclear power plants, which require the control systems to deal with wide changes in the operating conditions of the plant. However some unexpected scenarios or unusual events in the system mean the designed controller is sometimes simply 'overwhelmed' and a loss of performance and stability might occur. Examples of these unexpected scenarios are faults, failures or system 'damage', which are typically not considered in the controller design process.

The problem of achieving some level of performance and stability in the case when these unexpected scenarios occur, especially for safety critical systems (e.g., chemical and nuclear power plants) and expensive autonomous systems (e.g., satellites and underwater remote operating vehicles (ROV)) requires a different strategy rather than just having a robust or adaptive controller (which only guarantees stability and performance for perturbations in the nominal plant). An example of a system which requires such a control strategy is the problem of increasing the survivability of an aircraft when faults or failures to the actuators/sensors or structural damage occurs during a flight. In such a situation the aircraft requires some 'emergency' strategy to allow the pilot to safely land the aircraft. This challenge has motivated a strategy widely known in the literature as *fault tolerant control* (FTC).

Many different control paradigms have been applied to the problem of FTC. Examples of some of the existing control approaches can be found in Table 1.1, whilst Table 1.2 shows different systems that FTC has been applied to. In this book, the ad-

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Table 1.1 An example of existing approaches in FTC (adapted from [294])

Design approaches	References
Model-reference adaptive control	[142, 143, 230, 292]
Adaptive control	[14, 76, 143]
Multiple model switching and tuning	[10, 30, 41, 109, 111, 148, 195, 196, 253]
Interactive multiple model	[149, 170, 214, 284, 290]
Gain scheduling	[165]
Linear parameter varying systems	[16, 105, 182, 185, 215, 223, 224, 273]
Model predictive control	[176–178, 220]
Pseudo-inverse method	[106, 132, 187, 206, 284]
Control allocation	[29, 31, 37–39, 63, 89, 122, 127, 222]
Dynamic Inversion	[137, 138, 144, 172, 249, 250]
Robust control e.g., $\mathcal{H}_\infty$	[178, 228]
Sliding mode control	[85, 127, 256]

Table 1.2 An example of applications of FTC and FDI (adapted from [294])

Applications	References
Aircraft	[16, 40–44, 105, 185, 230, 233, 253]
Spacecraft	[68, 108, 137]
Automotive	[115, 154]
Engine and propulsion control	[40, 155, 202, 253]
Chemical/petrochemical plants	[176]
Robots	[198]

vantages of FTC will be demonstrated on aircraft systems as an example of a safety critical plant.

1.1 Motivation for Fault Tolerant Control Systems

The safety of aircraft passengers has been and will continue to be an important issue in the commercial aviation industry. Figures 1.1 and 1.2 represent some recent civil aviation safety statistics. Although the number of flights has doubled since 1980, the number of fatal accidents has been maintained over the years, and in fact decreased during the period from 1999–2003 [1]. This is contributed to by many factors, such as the stringent safety measures imposed on the aircraft and the implementation of important safety technology. Furthermore, all pilots undergo extensive training to help them to react to unforeseen difficulties which may arise during a flight. Figure 1.2 shows that 'controlled flight into terrain' (CFIT) and 'loss of control in flight' are the two most important occurrences and involve the most fatalities [1].

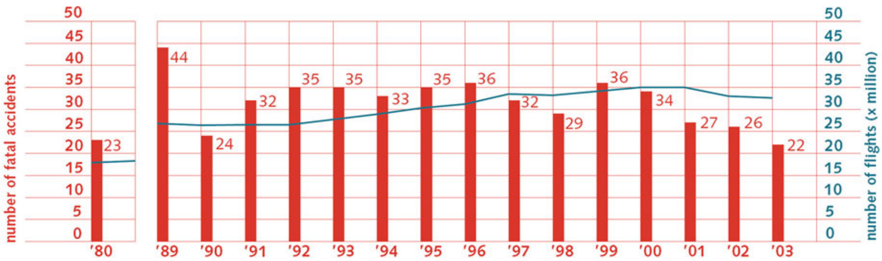

Fig. 1.1 Number of flights and fatal accidents (figure from [1])

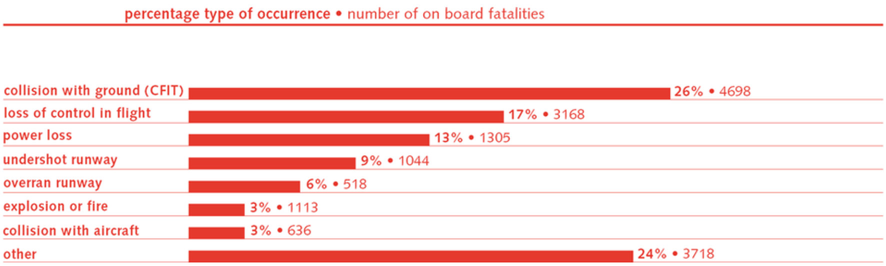

Fig. 1.2 Type of occurrences and fatalities (figure from [1])

Loss of control during flight is one of the motivating factors for fault tolerant control: the idea is to increase the 'flyability' of aircraft in the event of faults, failures or airframe damage. Learning from previous incidents, where pilots successfully landed crippled aircraft—such as Flight 232 in Sioux City, Iowa 1989,[1] the Kalita Air freighter in Detroit, Michigan, October 2004 (Fig. 1.4)[2] and the DHL freighter incident in Baghdad, November 2003 (Fig. 1.3)[3]—suggests that in many cases, the damaged aircraft is still 'flyable', with sufficient functionality to allow the pilot to safely land the aircraft.

It has been argued that with pilot skill and a fault tolerant control system, several accidents could have been avoided. For example, a recent report [40, 253] described a NASA experiment in which, by clever manipulation of thrust (in the event of total hydraulic loss), it was possible to land the 'crippled' plane. Pilot reviews and comments after the flight test indicate that fault tolerant control did help the pilot control the crippled plane when compared to pilot control alone [40, 253]. Although the work by NASA on propulsion controlled aircraft successfully handles total hydraulic loss, it is not sufficient to solve the general problem of fault tolerant control for aircraft, especially when other control surfaces are still functional or when dealing with structural damage and aerodynamic change (which for example occurred

[1] Flight 232 suffered tail engine failure causing total loss of hydraulics [41, 109].

[2] The freighter shed engine No. 1, but the crew managed to land safely.

[3] The A300B4 was hit by a missile and lost all hydraulics, but landed safely [41].

(a) (picture taken from [80])

(b) (picture: JetPhoto.net/DK (c))

(c) (picture: wikipedia)

(d) (picture: aviation-safety.net)

Fig. 1.3 DHL A300B4 emergency landing after being hit by missile in Baghdad, 2003

(a) (picture: pprune.org)

(b) (picture: airdisaster.com)

Fig. 1.4 Kalita Air emergency landing after losing one engine, 2004 in the ELAL flight 1862 Bijlmermeer incident [8]) or when dealing with control surface jams or runaways (for example flight 427, near Aliquippa, Pennsylvania in 1994 [9]).

1.2 Sliding Modes for FTC and FDI

Generally speaking, fault tolerant control (FTC) schemes are classified as either passive or active. Passive schemes operate independently of any fault information and basically exploit the robustness of the underlying controller. Such schemes are usually less complex, but in order to cope with 'worst case' fault effects, are conservative. Active fault tolerant controllers react to the occurrence of faults, typically by using information from a fault detection and isolation (FDI) scheme, and invoke some form of reconfiguration. This represents a more flexible architecture. Early publications focussed on so-called projection methods whereby if a particular fault was detected and identified, a corresponding control law from a pre-specified and pre-computed set of controllers, was selected and switched online. Subsequent methods have tended to focus on online adaption or online controller synthesis. Reconfiguration is usually necessary in the event of severe faults such as total failures in actuators/sensors. For example, if a sensor or actuator fails totally, no adaptation within that feedback loop can recover performance without modification to the choice of actuators and sensors coupled via the controller (i.e., reconfiguration). Fault tolerant control may be considered to be at the intersection of a number of research fields, and is essentially an open problem. Unsurprisingly many robust control paradigms have been used as the basis for fault tolerant controllers. These include LQR, adaptive, $\mathcal{H}_\infty$, QFT, model-following, neural networks, pseudo-inverse methods, Nonlinear Dynamic Inversion (NDI), multiple model approaches and MPC (see Table 1.1).

The possibilities of exploiting the inherent robustness properties of sliding modes for fault tolerance has previously been explored for aerospace applications and the work in [127] argued that sliding mode control has the potential to become an alternative to reconfigurable control. This is due to the inherent robustness properties of sliding modes to a certain class of uncertainty, including its ability to directly handle actuator faults without requiring the fault to be detected and without requiring controller reconfiguration. Despite its robustness property in handling actuator faults, sliding mode control (as with most other controllers) cannot handle total actuator failures. Some of the current research attempting to solve this problem has assumed that exact replication of the failed actuator is available [58]. However this is only applicable to a few over actuated systems. This is one aspect that will be explored in this book.

Observer-based methods are the most popular form of model-based fault detection filter. Typically (in linear observer schemes) the output estimation error, formed as the difference between the measured plant output and the output of the observer, is scaled to form a residual. During fault-free operation, this residual should be 'zero'