# 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.

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