

Chapter 2

Review

This chapter reviews some of the most relevant fault-tolerant flight control systems that can be found in the literature. Since the terminology used in this field is not unique and differs among authors, the chapter starts with a brief definition of some terms and expressions frequently used throughout this book.

2.1 Definition of Fault-tolerant Systems

Since the systems of interest are said to be fault-tolerant, let us first clarify the terminological distinction between a *fault* and a *failure* [1].

2.1.1 *Fault*

“A fault is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition.” [1]

Based on this definition, a fault corresponds to an abnormal behavior of the system, which may not affect the overall functioning of the system but may eventually lead to a failure (defined below). Finally, a fault may be small or hidden, and therefore difficult to detect and estimate.

For example, consider the temperature of an engine. If this temperature exceeds a certain accepted limit, say 100°C, there is a fault in the system. Although this excessive temperature does not prevent the engine from working properly for a while, it may eventually damage components of the engine and possibly lead to its breaking down.

In this book, an actuator fault corresponds to any abnormal behavior. This includes bias or loss of effectiveness as shown in Fig. 2.1d.

A sensor fault occurs as soon as the measurement data deviate from the real physical measured process by more than the noise uncertainty. Bias, excessive noise, or wrong scaling factors are also classified as sensor faults, as shown in Fig. 2.2.

2.1.2 Failure

“A failure is a permanent interruption of a system’s ability to perform a required function under specified operating conditions.” [1]

Resulting from one or more faults, a failure is therefore an event that terminates the functioning of a unit in the system. On an aircraft, actuators are used to deflect control surfaces such as ailerons, elevators, and rudders, and also to actuate the engine throttle or the landing-gear mechanism. An actuator is declared failed when it can no longer be used in a controlled manner.

For a control surface, there are two major types of failures [2]. As shown in Fig. 2.1a, the control surface may become ineffective and float at the zero-moment position. The control surface can also be locked at any arbitrary intermediate position (Fig. 2.1b) or reach and stay at the saturation position as shown in Fig. 2.1c.

Mechanical failures may also happen. This is the case when the mechanical link between the control surface and its corresponding actuator or servo breaks. The engine may also fail.

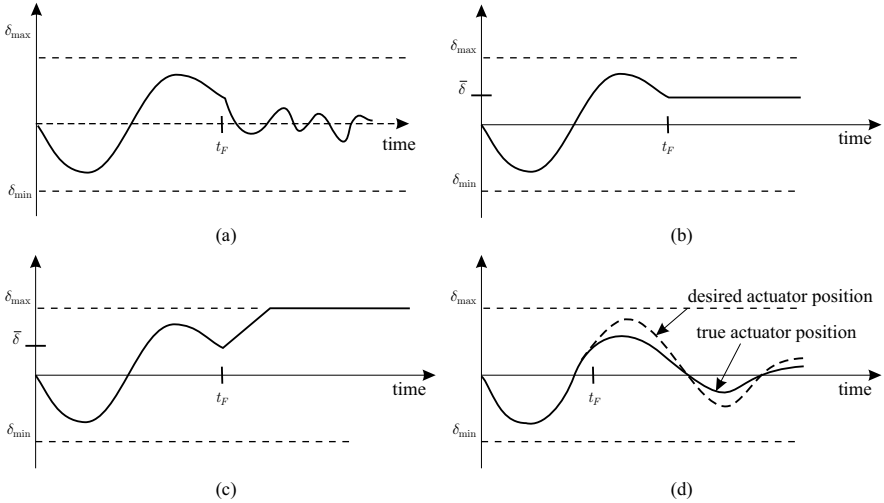


Fig. 2.1 Several types of actuator failures: (a) floating around trim; (b) locked-in-place; (c) hard-over; and (d) loss of effectiveness (actuator fault occurring after t_F)

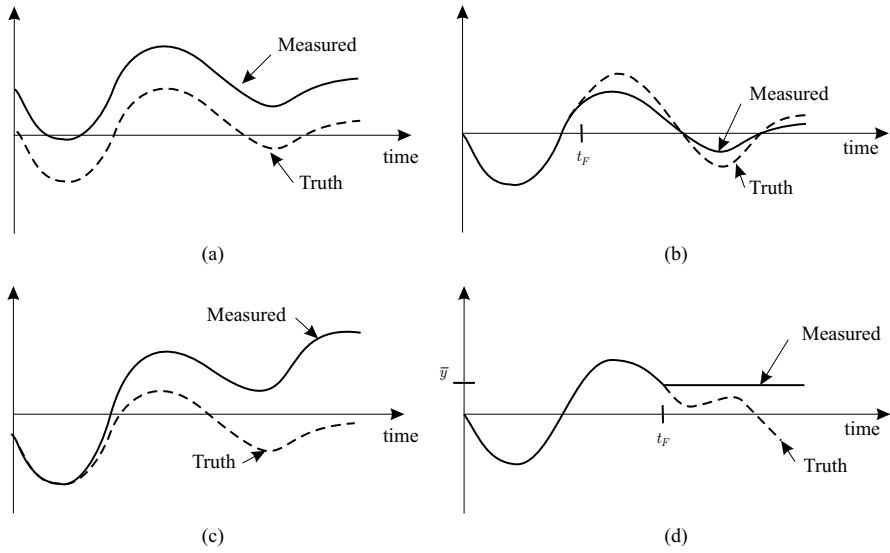


Fig. 2.2 Several types of sensor faults: (a) sensor bias; (b) loss of accuracy or calibration error; (c) sensor drift; and (d) frozen sensor (occurring after t_F)

Finally, there are many sources of possible irreversible damage to the aircraft that may be classified as structural failures. They correspond to the scenarios where a piece of the aircraft is missing, such as an aileron, a tail rudder, an elevator, or part of a wing.

The reconfigurable flight control system of this book is capable of detecting faults in the system (which are more difficult to detect than failures) and is able to adequately compensate for failures (which is more difficult than to only accommodate faults).

2.1.3 Fault-tolerant Control System

A fault-tolerant control system is capable of controlling the system with satisfactory performance even if one or several faults, or more critically, one or several failures occur in this system. Fault-tolerant control systems may be regrouped into two main families: passive fault-tolerant controllers and active fault-tolerant controllers.

2.1.3.1 Passive Fault-tolerant Controllers

In a passive fault-tolerant controller, deviations of the plant parameters from their true values or deviations of the actuators from their expected position

may be efficiently compensated by a fixed robust feedback controller [3–5]. However, if these deviations become excessively large and exceed the robustness properties, some actions need to be taken. Also, if deviations occur at the sensor side, inevitable deviations from the reference command signals will happen. Therefore, an active fault-tolerant control architecture is needed in order to achieve extended fault-tolerance capability.

2.1.3.2 Active Fault-tolerant Controllers

An active fault-tolerant controller usually contains a separate module: an FDI system that monitors the health of the aircraft. The FDI system informs a supervision module of the seriousness of the fault/failure or damage. Based thereon, the supervision module may decide to reconfigure the flight controllers, the guidance system, and the navigation system.

There are also two families of FDI systems, namely passive FDI and active FDI systems. Passive FDI systems “wait” until a fault or failure occurs [6], whereas active FDI systems will artificially excite the aircraft, either by flying health-check maneuvers [7, 8] or by injecting test signals in the actuator commands and then assessing the individual health status of actuators and sensors [8–15].

In this book, an active fault-tolerant control system has been developed, which contains an active nonlinear FDI system and robust nonlinear controllers in all of the control loops of the autopilot. Furthermore, a supervision module has been designed that is capable of reconfiguring the control allocation process described in Chap. 5, the controllers presented in Chaps. 7 and 8, and the guidance system explained in Chaps. 9 and 10.

2.1.4 *Dealing with Faults and Failures in Practice*

In this book, there will be an emphasis on actuator faults and failures. Indeed, a sensor failure does not modify the flying performance of the aircraft. The sensor failure can be handled either by using a redundant sensor if available, or by reconstructing the missing measurement data with the knowledge of the plant and the measurement data furnished by the remaining sensors [16]. The FDI method presented in this book is also capable of reconstructing the data of a failed attitude sensor [17]. However, as soon as there is an actuator failure or any damage to the airframe, the flying qualities of the aircraft inevitably degrade, and immediate action must be taken to preserve the aircraft’s integrity. This is the focus of this book.

2.2 Challenges of Designing Reconfigurable Control Systems

There are many challenges when designing a reconfigurable flight control system and the difficulties may be categorized as follows:

2.2.1 Difficulties of Designing Reliable FDI Systems

A reliable FDI system provides accurate information about the health status of the aircraft. In order to achieve such a result, the FDI system needs to be robust against external disturbances, model uncertainties and sensor noise. In addition, the FDI system should not trigger false alarms and should still be sufficiently sensitive to detect the faults.

Robustness is a fundamental issue in the performance of FDI systems and reconfigurable flight controllers [18, 19]. FDI systems may experience significant performance reduction if model uncertainties are not properly considered. A robustness analysis framework for failure detection and accommodation systems is provided in [18] and [20].

2.2.2 Interaction Between Flight Controllers and FDI Systems

It is often the case that a reconfigurable flight control system incorporates an FDI system and a flight controller. The FDI system monitors the aircraft's behavior and identifies relevant parameters that are usually used by the flight controller to synthesize the control commands. Therefore, the performance of the flight controller is dependent on the results provided by the FDI system and *vice versa*. Thus, the interactions between these two systems should be rigorously investigated.

The following observation is made in [19]: “it is fairly common for integration of failure detection and accommodation systems to be problematic if they are designed separately”.

Challenges exist when some aircraft parameters need to be identified during the flight in real time and under feedback control [21]. This task is even more difficult and delicate when an actuator or a sensor fault happens. Moreover, the robustness of the flight controller can mask some aircraft faults and failures and make the detection problem more difficult.

There exist already many examples of integrated fault-tolerant control, sometimes referred to as IFTC [6, 19, 22–25].

New generations of reconfigurable flight control systems will not only rely on a fault-tolerant controller, but will include complete and integrated systems that reconfigure the flight controllers, adapt the guidance system, and reshape on-line the vehicle trajectories [25]. This book also provides an example of such a complete reconfigurable system applied to a small UAV.

2.2.3 Other Practical Challenges

Usually, the flight control system relies on some nominal values for the mass, the moments of inertia and the aerodynamic coefficients to generate the control signals. When the aircraft experiences an actuator failure or airframe damage, the aircraft becomes asymmetric. It is thus not trivial to determine which of these parameters need to be (on-line) re-estimated to keep good flying performance.

It is often the case that the available on-board processing power is limited, in particular for small or micro UAVs. The design of a reconfigurable flight controller is therefore a tradeoff between performance, complexity and available processing power.

Finally, challenges are many when the fault diagnostic, the reconfiguration of the control system, the reconfiguration of the path plan or of the mission is to be done autonomously under limited or no human supervision.

2.3 Different Approaches for FDI Systems

Table 2.1 provides a list of common and recent techniques that are encountered in the literature for the design of FDI systems.

2.3.1 Trends in Filter Design for FDI System

More than a decade ago in the mid-1990s, several implementations of recursive least squares (RLS) algorithms were used in FDI systems and successfully flight tested. For example, the work by Ward *et al.* in [21] describes a computationally efficient real-time parameter identification and reconfigurable control algorithm. The identification algorithm is based on a modified sequential least-squares (MSLS) found in [61], the recursive version of which is found in [27]. The MSLS parameter identification algorithm is based on RLS techniques and incorporates additional constraints to take into account *a priori* information and to adjust the size of the data window used in the regressor of the filter [26].

Table 2.1 List of some recent and popular techniques used to design FDI systems for flight applications

Technique	Example of recent books/papers using this technique (ordered chronologically)
(Modified -) RLS	[21, 26–28]
KF (bank of -)	[29–35]
EKF (bank of -)	[11, 13, 34, 36, 37]
UKF	[38–41]
LPV filters	[42]
Interaction matrix	[43]
Particle filters	[44]
Neural networks	[7, 45–48]
Statistical methods	[1, 49]
Wavelet analysis	[3, 7]
H_∞	[6, 50–52]
Robust model-based system	[18, 53, 54]
Parity space approach	[1, 18, 55–57]
Unknown input observer	[58–60]

Many FDI filters have also been designed using mathematical models of the system being monitored. Model-based FDI methods have been enhanced using robust FDI techniques as defined by Chen and Patton in [18]. It consists of incorporating during the design of FDI systems the effects of disturbance signals, model uncertainties and measurement noise [53]. It is often the case that several model-based filters are organized in a bank in which one filter is sensitive to a specified failure but the other filters remain insensitive to that failure. A very recent example of this technique can be found in [54] where a robust fault diagnosis for a spacecraft attitude control system is designed.

Many different variants of Kalman filters (KFs) have been constructed for detecting and isolating faults or for state estimation and state reconstruction. The use of extended Kalman filters (EKFs) applied to nonlinear systems for FDI purposes has also gained recent interest in [11, 13, 34] and in this book. A recent paper presented a method that uses EKFs to estimate on-line the aircraft's aerodynamic parameters and the components of the wind velocity. These estimates are used to update the parameters of the flight controller [36].

The unscented Kalman filter (UKF) is among the latest extensions of Kalman-type filters and seems to provide remarkable results for systems that are particularly nonlinear. The paper by Campbell [40] discusses the implementation of a sigma point filter (SPF) which was originally introduced as the UKF [38], where the distributions are approximated by a finite set of points. It is used to estimate aircraft states and aerodynamic derivatives in

real time. This is a nonlinear estimation algorithm that can be performed on-line, which possesses robustness properties against parameter uncertainties, against filter tuning and initial conditions.

The discussion in [38] explains that the SPF has similar performance to a truncated second-order EKF but without the need to calculate the Jacobian matrices. A comparison between EKF and SPF can also be found in [39]. The main results of this paper indicate that the SPF filter has equal or better performance than an EKF for real-time estimation application for the following reasons: the SPF is more robust against initial uncertainties and against jumps in the data, is less sensitive to tuning of the process noise, is less susceptible to divergence, is more accurate from one time step to the next and, finally, requires equivalent computational load. Very recent contributions in [41] focused on a new formulation for the state update equation of the filter for improved accuracy.

Recently, linear parameter-varying (LPV) filters gained the attention of some researchers in the fault-tolerant control community. For example, a design of LPV-based FDI filters is found in [42]. An example of an H_∞ control law that minimizes command tracking errors under actuator fault occurrence combined with an FDI filter based on an affine LPV model of a Boeing 747 is found in [19].

2.3.2 Trends in Active Fault Detection

Better, faster, and more reliable actuator and sensor fault-tolerant systems are being designed by exploiting the concept of active fault supervision. This consists of injecting artificial signals in actuators in such a way that a robust and reliable fault diagnosis can be made even if the system is excited very slightly.

Very few papers have discussed this technique so far. The work published by Honeywell in 1998 [8] and 2001 [9] is among the first occurrences of using artificial exciting signals for FDI purposes. Test signals are injected into the null space of the inputs using redundant control surfaces such that these signals (ideally) cancel one another and thereby do not excite aircraft motion [9], but contribute to better fault diagnosis; see also [62].

In 2006, the use of artificial signals was demonstrated to improve significantly the performance of an FDI system based on the extended multiple model adaptive estimation (EMMAE) method [11, 13]. This method is described in Chap. 4 of this book and in [13]. In 2007, the authors of [12] suggested an adaptive fault-tolerant controller with self fault-diagnosis actuators. This is done by generating high-frequency signals for actuators with suspected failures, and minimizing the effects of those signals on the system state using the remaining healthy actuators.

Recent contributions in active fault-diagnosis utilizing artificial excitation signals can also be found in [14] and [15].

2.4 Different Approaches for Flight Control Systems

Table 2.2 provides a list of the most common techniques that are encountered in the literature for the design of flight control systems.

Table 2.2 List of some recent and popular techniques used to design flight control systems

Technique	Example of recent books/papers using this technique (ordered chronologically)
P, PD, PI, PID	[25, 37, 63]
H_∞ , LQ, LQG, LTR	[3–5, 64–67]
Dynamic inversion	[37, 47, 48, 62, 63, 68–74]
Quantitative feedback theory	[75, 76]
LPV	[77–79]
Model predictive control, Receding horizon	[4, 40]
Backstepping	[80–82]
Neural networks	[45–48, 74, 83]
Adaptive control	[4, 21, 29, 35, 84–86]
Model following	[4, 37, 47, 48]
Sliding mode control	[86–92]
Fuzzy logic	[4, 93]
Eigenstructure assignment	[4, 22, 94]

2.5 Techniques to Design Fault-tolerant Flight Control Systems

Table 2.3 provides a list of the most common techniques that are encountered in the literature for the design of fault-tolerant and reconfigurable flight control systems. Some of these techniques as described below.

Table 2.3 List of some recent and popular techniques used to design reconfigurable flight control systems

Technique	Example of recent books/papers using this technique (ordered chronologically)
Multiple model switching and tuning	[95, 96]
Multiple model adaptive control	[30, 32, 33, 35, 97]
Interacting multiple models	[44, 98]
Control allocation	[37, 47, 62, 82, 99–105]
Sliding mode control	[86, 90–92, 106–109]
Model predictive control	[40, 110]
Eigenstructure assignment	[22, 94, 98]
Model reference adaptive control	[28, 74, 84, 111]
Model reference + Dynamic inversion	[12, 25, 36, 37, 47, 48, 74, 84, 112]
Neural networks	[45–48, 74, 83]
Other recent fault compensation strategies	[113]

2.5.1 Multiple Model Techniques

2.5.1.1 Multiple Model Switching and Tuning

In the multiple model switching and tuning (MMST) technique shown in Fig. 2.3, the dynamics of each fault scenario are described by a dedicated model. Each model is paired with its respective controller. The control system is re-configured by choosing the model/controller pair that is the most appropriate at each time step.

A switching logic module computes for each model i a performance index J_i , which is a function of the error e_i between the model M_i and the measurement data vector y . The performance index J_i is of the following form:

$$J_i(t) = \alpha e_i^2(t) + \beta \int_0^t \exp[-\lambda(t - \tau)] e_i^2(\tau) d\tau \quad (2.1)$$

$$\alpha \geq 0, \beta > 0, \lambda > 0.$$

The coefficients α and β are responsible for the tradeoff between instantaneous and long-term contributions of the error e_i in the calculation of the index J_i . The coefficient λ is used as a forgetting factor.

The model M_i that produces the smallest performance index J is the closest to the current system, and therefore the controller K_i becomes active.

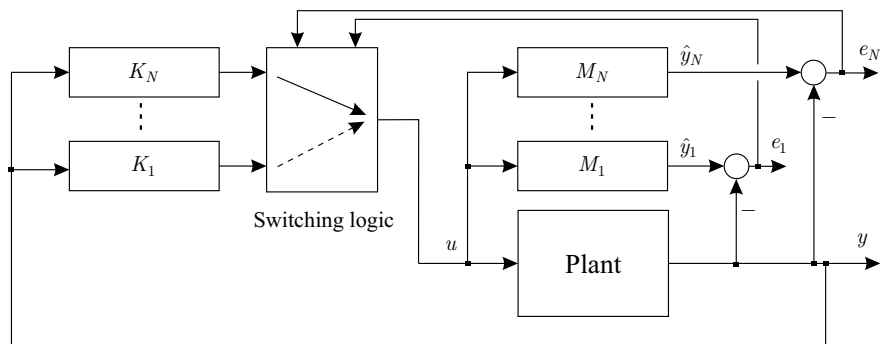


Fig. 2.3 MMST scheme

Most of the MMST reconfigurable schemes also include a tuning part, which is a separate identification algorithm that updates the parameters of the model M_i while the controller K_i is active.

The MMST technique has the advantages of being fast and usually stable if the actually occurring failures match the predefined fault scenarios. However, severe limitations of the method appear in practice as soon as an unmodeled failure is encountered or if multiple or structural failures occur. Moreover, the number of individual pairs of model/controller to be designed may become excessively large if the system is to successfully operate over a wide range of failure scenarios [95, 96].

2.5.1.2 Multiple Model Adaptive Estimation

Another approach to detect and isolate actuator or sensor faults is the multiple model adaptive estimation (MMAE) method [114] as depicted in Fig. 2.4. It is based on a bank of KFs running in parallel, each of which is matching a particular fault status of the system. A hypothesis testing algorithm uses the residuals from each KF to assign a conditional probability to each fault hypothesis. As one may expect, the computational load is quite intense. Therefore, the on-line use of this method was impractical for a long time. However, with the more powerful processors now available this method has regained appeal in many applications.

Several papers have demonstrated how the MMAE method can be used in the context of FDI systems and control reconfiguration for aircraft [30–32] and underwater vehicles [33]. The advantages and limitations of the MMAE method are discussed in detail in Chap. 4, where an extended and nonlinear FDI method is designed based on the MMAE technique.

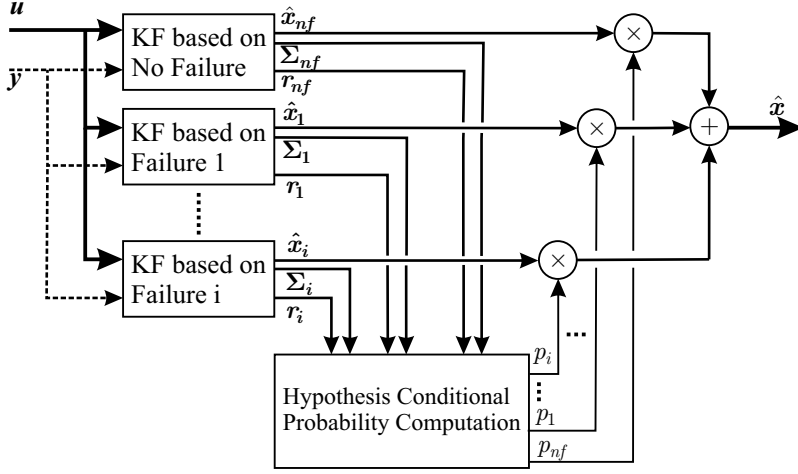


Fig. 2.4 Classical MMAE scheme

2.5.2 Control Allocation Techniques

Control allocation techniques are described in detail in Chap. 5. Briefly stated, the flight control system generates a virtual control command $\mathbf{C}_v = [C_L \ C_M \ C_N]^T$ in terms of the desired roll, pitch, and yaw torques. This virtual command \mathbf{C}_v is passed to the control allocator, which is provided with each actuator's position limits and effectiveness to produce any torque component of the \mathbf{C}_v vector. An algorithm is computed on-line to optimally generate the control signals for the actuators [99, 100, 103].

The biggest advantage of using a control allocation technique is that actuator failures can be compensated without the need for modifying the flight control laws [82]. Moreover, actuator constraints, such as deflection limits and motion rates, can be taken into account by the control allocator when the virtual command \mathbf{C}_v is “distributed” over the actuators. Finally, the deflection of each actuator can be chosen by the control allocator to optimize some criteria, such as total drag, total deflections, or to prioritize some actuators.

However, as explained in [96], control allocation techniques may have the following disadvantage: “the dynamics and limitations of the actuators after a failure are not taken into account in the control laws. This means that the controller will still attempt to achieve the original system performance even though the actuators are not capable of achieving it”. Chapters 8 and 10 explain how these disadvantages have been overcome in this book.

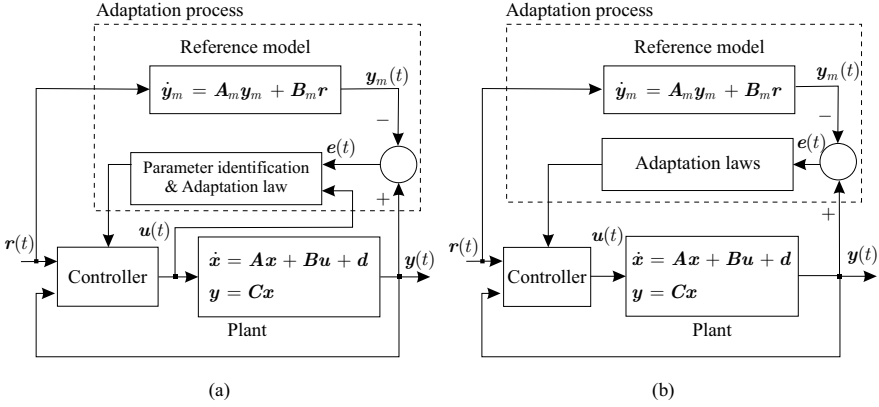


Fig. 2.5 MRAC scheme: (a) indirect controller parameter adaptation; and (b) direct controller parameter adaptation

2.5.3 Model Reference Adaptive Control

Model reference adaptive control (MRAC) [111, 115] is a method that can be utilized when tolerance to damage or structural failures is required. This technique is also often used as a final stage of a complex control system combining several algorithms. The goal is to have the output of the plant under consideration follow the output of a reference model.

The linearized plant under consideration is of the form

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{d}, \\ \mathbf{y} &= \mathbf{C}\mathbf{x},\end{aligned}\tag{2.2}$$

where the system state vector is $\mathbf{x} \in \mathbf{R}^n$, the control input vector is $\mathbf{u} \in \mathbf{R}^p$, and the measurement vector is $\mathbf{y} \in \mathbf{R}^k$. The reference model is of the form

$$\dot{\mathbf{y}}_m = \mathbf{A}_m \mathbf{y}_m + \mathbf{B}_m \mathbf{r},\tag{2.3}$$

where the output vector of the reference model is $\mathbf{y}_m \in \mathbf{R}^k$ and the reference signal vector is $\mathbf{r} \in \mathbf{R}^l$. The dynamics matrix $\mathbf{A}_m \in \mathbf{R}^{k \times k}$ and $\mathbf{B}_m \in \mathbf{R}^{k \times l}$ can be chosen arbitrarily, but \mathbf{A}_m must be stable [115].

In order to have the output of the plant follow the output of the reference model, the parameters of the controller are adapted by some adaptation laws as shown in Fig. 2.5. There are two types of adaptation, namely the indirect and the direct adaptation.

In the indirect adaptation, the matrices \mathbf{A} , \mathbf{B} , and the vector \mathbf{d} are first estimated, for example using a least squares algorithm. In a second step, based on the estimates $\hat{\mathbf{A}}$, $\hat{\mathbf{B}}$ and $\hat{\mathbf{d}}$, the controller parameters are computed

by the adaptation laws such that the closed-loop system matches the desired dynamics of the reference model.

In the direct adaptation, the controller parameters are directly adapted such that the plant tracks the reference model.

However, the MRAC technique has some limitations. The adaptation laws require an estimation algorithm to track certain parameters of the system. It is therefore necessary that these system parameters evolve slowly enough in order that the estimation routine can track them properly. Faults or failures, however, may cause abrupt changes in the values of the system parameters. During the transient phase, in which the adaptive algorithm identifies the new faulty plant, it is not guaranteed that the controller can stabilize the system. Therefore, the MRAC technique is usually not used on its own but in combination with other algorithms in a more complicated fault-tolerant control architecture [25, 84].

2.5.4 Other Reconfigurable Control Methods

As shown in Table 2.3, there are other methods to design a reconfigurable flight control system. For instance, the *eigenstructure assignment* is used to reconfigure the feedback control laws in [98] and [94]. In *model predictive control* (MPC), the constraints on actuators or on any other state variable are systematically taken into account during the generation of the control signals [110]. A recent robust nonlinear MPC for low level aircraft control is presented in [40].

Sliding mode control has been investigated in [86, 90, 106–109]. The sliding mode control technique possesses some insensitivity and robustness properties to certain types of disturbance and uncertainty, which is an appealing feature for fault-tolerant flight control [87, 88]. The ability of sliding mode control to maintain the aircraft desired performance in case of faults without requiring an explicit FDI system makes it an other example of a passive approach to fault-tolerant control. Recent developments that employ sliding mode control for fault-tolerant control of a civil aircraft for both sensor and actuator faults are described in [89] and [91].

Other popular reconfigurable flight control systems use adaptive feedback linearization via artificial neural networks [45] or via on-line parameter identification methods [84]. New combinations of model reference and inverse dynamics controllers have been discussed in [84] and [25], and very recently in [12, 36, 74, 112, 116–118] and in this book.

2.6 Reconfigurable Guidance Systems

Over the last two decades, many path-planning algorithms have been investigated, especially for ground robots, single UAV, and more recently for a formation of UAVs. Among the methods used in path planning, we can mention the *probabilistic road maps* (PRM) method [119], which explores all the possible paths within the space surrounding the vehicle and finally selects the lowest cost route. However, the computational load makes the PRM method impractical for real-time path planning in small UAVs. An extension to the PRM method has recently been presented in [120]. It is called modified *rapidly-exploring random trees*, which is capable of efficiently searching for feasible paths in the space while taking into account constraints from the vehicle performance. However, efforts are still going on to implement an on-the-fly path-replanning system as pop-up obstacles are discovered or when the performance of the vehicle degrades.

There are other methods based on *potential field functions*. However, the primitive forms of potential field functions present some difficulties when choosing an appropriate potential function, and the algorithm may be stuck at some local minimum [121]. Since then, a whole family of potential field methods with superior performance has been developed. They are known as *navigation functions* [122, 123]. Other path-planning techniques are based on optimization methods, such as *mixed integer linear programming* or MPC techniques [124], which still involve intensive computations.

In this book, a reconfigurable guidance algorithm for a UAV is presented, which newly combines the lateral guidance control law from [125] and [126], originally designed for UAVs tracking circles for mid-air rendez vous, with a new, simple adaptive path-planning algorithm, which takes advantage of the curve path-following property of the above-mentioned lateral guidance law [127–130].

2.7 Real Flight Tests

One of the biggest challenge in UAV research is to fly test the algorithms developed. Several successful flight tests occurred over the past few years.

At the end of the 1990s, a significant milestone in the development of reconfigurable control systems was the flight testing with a NASA F15 aircraft of the so-called Self Repairing Flight Control System, which achieved failure and damage tolerance through an indirect adaptive reconfigurable flight control architecture that used an explicit FDI system to perform on-line damage and fault detection and estimation using hypothesis testing techniques associated with a bank of KFs [29].

Using an alternative approach based on an indirect adaptive control architecture, during the summer 1996, a series of flight tests demonstrated an

adaptive approach to reconfigurable flight control called Self Designing Controller. The results of the flight tests are reported in [21]. The fault scenario corresponded to the landing of an F-16 with a simulated missing elevator.

Another successful flight test was conducted as part of the Reconfigurable Systems for Tailless Fighter Aircraft also known as the RESTORE program. The technology used in this program combined a dynamic inversion control law in an explicit model-following framework. A neural network was also used for on-line learning of selected aircraft parameters and used in the feedback linearization loops [47, 48].

Flight tests of the US Air Force's Integrated Adaptive Guidance and Control program developed for the Boeing X-40A are reported in [25].

Flight testing of a simple reconfigurable control system on an autonomous model aircraft is reported in [28].

A number of flight tests of reconfigurable control systems were carried out as part of the Defense Advanced Research Projects Agency (DARPA) Software Enabled Control program on two unmanned combat aerial vehicles (UCAVs), namely the Boeing T-33/UCAV and Boeing X-45 UCAV [52].

NASA Langley Research Center is also actively involved in developing and testing reconfigurable systems for the new generation of re-entry vehicles, commercial aircraft and small UAVs [111, 131]. Several recovery systems and technologies were developed as part of the Aviation Safety program. High risk flight tests were conducted utilizing a dynamically scaled transport aircraft that has been developed at the NASA Langley Research Center as part of the Airborne Subscale Transport Aircraft Research testbed [132, 133].

The NASA/Boeing X-36 Tailless Fighter Agility Research Aircraft program successfully demonstrated the tailless fighter design using advanced technologies to improve the maneuverability and survivability of possible future fighter aircraft.

At the end of 2004 and beginning of 2005, the US Air Force and Boeing Company conducted a flight test of a modified MK-82 weapon at Eglin Air Force Base, which was controlled with a direct adaptive model reference flight control system that is capable of learning on-line some aerodynamics parameters with a neural-network algorithm similar to the one used in the RESTORE program [85].

More recently, the long endurance SeaScan UAV has been developed by the Insitu Group for weather reconnaissance and has recently been deployed in Iraq [40].

Finally, Honeywell Research Laboratories, Barron Associates, Inc., Scientific Systems Company, Inc., *etc.*, are among the companies actively involved in designing and flight testing fault-tolerant control systems.

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