# Chapter 1
# Introduction

## 1.1 FD and FTC Against Actuator and/or Sensor Faults

With the development technology, modern control systems, such as flight control systems, become more and more complex and involve an increasing number of actuators and sensors. These physical components may become faulty which may cause system performance deterioration, may lead to instability that can further produce catastrophic accidents.

To improve system reliability and guarantee system stability in all situations, FD and fault accommodation methods have become attractive topics which received considerable attention during the past two decades as it can be attested by the abundant literatures [1–20].

Fault diagnosis including fault detection and isolation (FDI) [1, 6–9, 20] is used to detect faults and diagnosis their location and significance in a system [1]. It has the following tasks: fault detection, fault isolation and fault estimation. Fault detection is to make a decision, e.g., faults occur in the controlled systems or not. Fault isolation is used to determine the location of the faults, namely, which physical component has become faulty. The last task in FD is to estimate the size of the fault.

Fault tolerant control aims at preserving the functionalities of a faulty system with acceptable performances. FTC can be achieved in two ways, namely, passive and active ways [1]. Passive FTC uses feedback control law that is robust with respect to possible system faults [21–33]. Generally speaking, passive FTC is more conservative [1]. In order to relax the conservatism of the passive FTC approach, active FTC method is developed. Active FTC relies on a FD module process to monitor the performance of the controlled system, and to detect, isolate and estimate the faults in the controlled system [34–45]. Accordingly, the control law is reconfigured online.

In recent years, by using adaptive control technology, various FD and FTC approachers including passive and active FTC have been developed, and abundant results on adaptive FD and FTC can be found in literature [21–45].

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It is well known that, among the faults occurred in the controlled systems, actuator and sensor faults are common. In practical application, actuator and sensor faults have two kinds of faults, namely, bias faults and gain faults [46–52]. Bias fault model can be described as:

$$\begin{cases} Actuator\,fault: & u^f(t) = u(t) + f_u(x,u,t), \quad t \geq t_f \\ Sensor\,fault: & y^f(t) = y(t) + f_y(y,t), \quad t \geq t_f \end{cases} \tag{1.1}$$

where $t_f$ is an unknown fault occurrence time; $u$ and $u_f$ denote actuator input and output, respectively; $y$ and $y_f$ denote system output and actual obtained system output, respectively; $f_u(x,u,t)$ and $f_y(y,t)$ denote actuator and sensor fault, respectively, which are commonly assumed to be unknown but bounded signal. Actuator and sensor gain faults have the following form,

$$\begin{cases} Actuator\,fault: & u^f(t) = (1-\rho_u(x,u,t))u(t), \quad t \geq t_f \\ Sensor\,fault: & y^f(t) = (1-\rho_y(y,t))y(t), \quad t \geq t_f \end{cases} \tag{1.2}$$

where $t_f$ denotes an unknown fault occurrence time; $u$ and $u_f$ denote actuator input and output, respectively; $y$ and $y_f$ denote system output and actual obtained system out, respectively; $0 \leqslant \rho_u(x,u,t) \leqslant 1$ and $0 \leqslant \rho_y(y,t) \leqslant 1$ are unknown, which denote the remaining control rate and measurable part, respectively.

Recently, an integrated fault model is reported, which contains the above two kinds of faults [52, 53]. It can be uniformly described as:

$$\begin{cases} Actuator\,fault: & u^f(t) = (1-\rho_u(x,u,t))u(t) + f_u(x,u,t), \quad t \geq t_f \\ Sensor\,fault: & y^f(t) = (1-\rho_y(t))y(t) + f_y(t), \quad t \geq t_f \end{cases} \tag{1.3}$$

Very recently, a so-called infinite-number-faults model was reported [60], which can be described as follows:

$$\begin{cases} Actuator\,fault: & u^f(t) = (1-\rho_u(x,u,t))u(t) + \sum_{j=1}^{p_u} f_{u,j}(x,u,t), \quad t \geq t_f \\ Sensor\,fault: & y^f(t) = (1-\rho_y(y,t))y(t) + \sum_{j=1}^{p_y} f_{y,j}(y,t), \quad t \geq t_f \end{cases} \tag{1.4}$$

where $f_{u,j}(t)$ $(j = 1, \ldots, p_u)$ and $f_{y,j}(t)$ $(j = 1, \ldots, p_y)$ denote bounded signal, $p_u$ and $p_u$ are known positive constants.

From (1.1)–(1.4), it is easily seen that the actuator and sensor faults have an affine-like appearance of control input and/or system output. That is to say, the fault can be expressed explicitly as gain and/or bias fault [54–56], which is called *modeled fault* (MF) in this book. Unfortunately, there exist some cases in practical applications where the faults cannot be expressed in the above affine-like form [57–59]. The fault model can be described as follows:

$$\begin{cases} Actuator\,fault: & u^f = f(x, u), \quad t \geq t_f \\ Sensor\,fault: & y^f(t) = f(y), \quad t \geq t_f \end{cases} \tag{1.5}$$

where $f(x, u)$ and $f(y)$ are two unknown nonlinear smooth function, with $t_f$ being unknown fault occurrence time. Obviously, fault model described by (1.5) has no the traditional affine-like appearance of control input and/or system output. The fault is called *un-modeled fault* (UMF).

Although abundant results on FD and FTC against actuator and/or sensor faults have been obtained in literature, FD and FTC for dynamic systems still need to be deeply investigated due to their academic meaning as well as practical one, and there exist many open problems to be solved, which is the topic of this book.

- FD and FTC against infinite-number-integrated-faults:
  In most of the existing works in literature only considered bias faults, while gain faults have not attracted enough attention. From the theoretical point of view, it is possible that time-vary bias fault and time-vary gain fault simultaneously occur in the controlled systems. Further, the number of the faults occurred in systems maybe infinite. Hence, it is necessary to propose a novel infinite-number-integrated-fault model and design corresponding FD and FTC algorithms. In addition, the denominator of the fault-tolerant control input contains the estimation of the gain fault. If the denominator is equal to zero, a controller singularity occurs. Hence, controller singularity should be considered, and a novel FTC scheme must be designed to avoid the singularity problem.
- Multi-type multi-fault isolation:
  In the practical applications, multiple type multiple faults maybe simultaneously occur in the controlled systems. However, most of the results on FD and FTC in literature works under the restrictive condition that only one actuator fault occurs at one time. What's more, the results cannot be easily extended to the case where multiple actuator faults simultaneously occur. Therefore, it is a need for such case to design a novel FD algorithm to isolate multiple faults occurred simultaneously.
- FD and FTC against un-modeled fault:
  Since un-modeled fault has no traditional affine-like appearance of control input or system output, the results concerning on MF cannot be extended directly to FTC against UMF. Under some restrictive conditions, some researchers investigated the problem of FTC against UMFs, and only a few results were obtained in literature. In [57], the problem of adaptive FTC for nonlinear systems with actuator MF was investigated. However, the results are only applicable to second-order nonlinear systems rather than more general high-order systems, which limit their practical applications. In [58, 59], robust detection and isolation schemes for UMFs were addressed. However, these FDI schemes worked under the condition that the system state variables and control inputs were bounded before and after the occurrence of a fault, which is too restrictive. In addition, the UMF was assumed to be a known function about control input and system state with an unknown gain.

Hence, how to control more general high-order nonlinear systems with UMFs is still an important and open problem, which motivates us for this study.

- Computation complexity in backstepping design procedure:
  For the unknown nonlinear systems in or transformable to parameter strict-feedback form, adaptive backstepping technique is a powerful tool. At standard backstepping design procedure, analytic computation of the higher derivatives of virtual control signals is necessary, which leads to a so-called computation complexity especially when the system dimension increases. Hence, how to reduce the computation becomes crucial issue in controller design.

## 1.2 Fault Detection for Time-Delay Systems

Time delay phenomenon often exists in the practical applications because of information transmission. It has been proven that such time delay will causes the performance degradation of the controlled systems, even instability. Hence, the control problem of time delay systems, including FTC, always is a hot topic Over the past decade [61–73]. Stability analysis of the time delay systems can be divided into two classes: time-dependent and time-independent results. The former is dependent on the size of time delay, while the latter does relay on thecite time delay. Generally speaking, time-dependent results are more conservative than the time-independent results.

Recently, FD and FTC for the time delay systems has drawn wide attentions [74–82, 87]. In order to compensate for these faults, various fault-tolerant control (FTC) methods are proposed. Among these FTC methods, active FTC methods is more common, important and useful. Fault detection [83–86] is the first and important step in active FTC method. For time delay systems, however, most of the FD observers proposed in literature have a major shortcoming that the fault detection observers contain the unknown time delay terms. For example, consider a simple system

$$\begin{cases} \dot{x}(t) = Ax(t) + A_d x(t-d) + Bu \\ y(t) = Cx(t) \end{cases} \tag{1.6}$$

where $x,\ y$ and $u$ denote state, output and control input, respectively; $A,\ A_d,\ B$ and $C$ are known real matrices with appropriate dimensions; time delay $d$ is a constant. In most of the existing results such as [9], fault detection observer often is designed for (1.6) as follows:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + A_d\hat{x}(t-d) + Bu + L(\hat{y}(t) - y(t)) \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \tag{1.7}$$

where $L$ is observer gain matrix, which will be designed. Notice that, the first equation in (1.7) contains time delay term $\hat{x}(t-d)$. Obviously, if $d$ is unknown, then observer (1.7) is not reasonable and does not work in the practical applications.

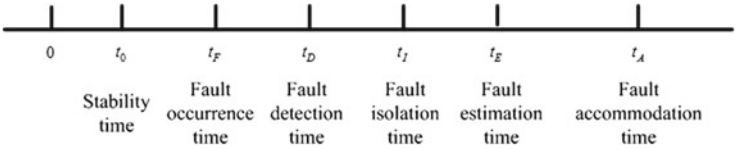

**Fig. 1.1** The fault diagnosis and accommodation time sequence

Hence, how to avoid the above shortcoming and design a proper observer for time delay systems becomes important and practically useful.

## 1.3 Analysis of Time Delay Due to Fault Diagnosis

In general, active FTC framework includes the following steps: fault detection, fault isolation, fault estimation and fault accommodation. The fault diagnosis and accommodation time sequence can be seen in Fig. 1.1. From Fig. 1.1, it is easily seen that each step need some time. The time interval is called as *time delay due to FD* in this book.

Generally speaking, it is under the condition that the fault occurred in system can immediately be detected and isolated that an active fault tolerant control law is designed [91]. In fact, there is always some time delay. Furthermore, when a fault occurs, the faulty system works under the nominal control until the fault is detected, isolated and fault accommodation is performed. That is to say, the considered system is always controlled by the faulty actuators during $[t_F, t_A]$. Obviously, it will degrades the system performances even damage the system. However, its effect is not studied enough, and there are only few results reported in literature [88–91]. Hence, *the time delay due to FD* should be derived strictly, and its adverse effect on the system performance should also be analyzed and a proper solution to minimize its adverse effect is given.

## 1.4 Organization of the Book

This book presents several fundamental problems of FD and FTC for dynamic systems. Combining adaptive control technique with the other control techniques or approaches, a basic theoretical framework is formed towards the issues of FD and FTC of dynamic system. In order to conveniently reading this book, some preliminaries including same or similar lemmas are introduced in different chapters. This book contains ten chapters, which exploit several independent yet related topics in the detail.

Chapter 2 addresses the problem of fault tolerant control for T-S fuzzy systems with single actuator faults. A general actuator fault model with infinite number of faults is proposed, which integrates time-varying bias faults and time-varying gain faults. Then, sliding mode observers are designed to provide a bank of residuals for fault detection and isolation, and a novel fault diagnostic algorithm is proposed, which removes the classical assumption that the time derivative of the output errors should be known as in some existing work. Further, a novel fault estimation observer is designed. Utilizing the estimated actuator fault, an accommodation scheme is proposed to compensate for the effect of the fault.

Chapter 3 investigates the fault tolerant control problem of near space vehicle attitude dynamics with multiple actuator faults, which is described by a T-S fuzzy model. Firstly, an integrated state-dependant actuator fault model with infinite number of faults is proposed to simultaneously deal with state-dependent bias and gain faults. Then, sliding mode observers are designed to provide a bank of residuals for fault detection and isolation. Based on Lyapunov stability theory, a fault diagnostic strategy is proposed. Further, for the two cases where the state is available or not, two accommodation schemes are proposed to compensate for the effect of the faults.

Chapter 4 focuses on the problem of fuzzy adaptive tracking control for a class of uncertain nonlinear strict-feedback systems with actuator fault. The actuator fault is assumed to have not only time-varying gain fault but also time-varying bias fault. Combining command filtered backstepping design with the integral-type Lyapunov function and utilizing Nussbaum-type gain technique, an adaptive fuzzy fault-tolerant control scheme is proposed to guarantee that the resulting closed-loop system is asymptotically bounded with the tracking error converging to a neighborhood of the origin. The control scheme requires only virtual control and its first one derivative instead of them and their higher derivatives in backstepping design procedures.

In Chap. 5, we consider the problem of fault-tolerant dynamic surface control for a class of uncertain nonlinear systems with actuator faults and propose an active fault-tolerant control scheme. Using the DSC technique, a novel fault diagnostic algorithm is proposed, which removes the classical assumption that the time derivative of the output error should be known. Further, an accommodation scheme is proposed to compensate for both actuator time-varying gain and bias faults, and avoids the controller singularity. In addition, the proposed controller guarantees that all signals of the closed-loop system are semi-globally uniformly ultimately bounded, and converge to a small neighborhood of the origin.

Chapter 6 discusses the problem of fault-tolerant control for a class of uncertain nonlinear high-order systems with actuator faults, and propose an observer-based FTC scheme. Adaptive fuzzy observers are designed to provide a bank of residuals for fault detection and isolation. Using a backstepping approach, a novel fault diagnosis algorithm is proposed, which removes the classical assumption that the time derivative of the output error should be known. Further, an accommodation scheme is proposed to compensate for the effect of the fault, where it is not needed to know the bounds of the time derivative of the fault. The proposed controller guarantees that all signals of the closed-loop system are semi-globally uniformly ultimately bounded and converge to a small neighborhood of the origin by appropriately choosing designed parameters.

In Chap. 7, the problem of adaptive active fault-tolerant control for a class of nonlinear systems with unknown actuator fault is investigated. The actuator fault is assumed to have no traditional affine appearance of the system state variables and control input. The useful property of the basis function of the radial basis function neural network, which will be used in the design of the fault tolerant controller, is explored. Based on the analysis of the design of normal and passive fault tolerant controllers, by using the implicit function theorem, a novel neural networks-based active fault-tolerant control scheme with fault alarm is proposed. Comparing with results in literature, the fault-tolerant control scheme can minimize the time delay between fault occurrence and accommodation that is called the time delay due to fault diagnosis, and reduce the adverse effect on system performance. In addition, the FTC scheme has the advantages of a passive fault-tolerant control scheme as well as the traditional active fault-tolerant control scheme's properties. Furthermore, the fault-tolerant control scheme requires no additional fault detection and isolation model which is necessary in the traditional active fault-tolerant control scheme.

Chapter 8 discusses the problem of fault-tolerant control against actuator fault, derives the time spent at each steps in fault diagnosis which is called as the time delay due to fault diagnosis and quantitatively analyzes its effect on the faulty systems performance. A novel fault diagnosis algorithm is first proposed. The proposed fault tolerant controller guarantees that all signals in the closed-loop system are semi-globally uniformly ultimately bounded. What's more, the analytical expression of the time delay is derived strictly. Further, the quantitative analysis of system performance which is degraded by the time delay is developed, and the conditions that the magnitudes of the faults should be satisfied such that the faulty system controlled by the normal controller remains bounded even stable during the time delay are derived. In addition, the corresponding solution to the adverse effect of the time delay is proposed.

Chapter 9 investigates the fault detection of uncertain systems with unknown time-delay constant, and design a novel adaptive neural network-based fault detection observer, where not only the system states but also the unknown time delay can be estimated. Furthermore, comparing with the existing works where an asymptotic value is taken as an indicator to determine whether faults occur or not, a more efficient fault detection mechanism is proposed.

In Chap. 10, several future research directions are predicated.

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