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Bibliographical review on reconfigurable fault-tolerant control systems

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Abstract

In this paper, a bibliographical review on reconfigurable (active) fault-tolerant control systems (FTCS) is presented. The existing approaches to fault detection and diagnosis (FDD) and fault-tolerant control (FTC) in a general framework of active fault-tolerant control systems (AFTCS) are considered and classified according to different criteria such as design methodologies and applications. A comparison of different approaches is briefly carried out. Focuses in the field on the current research are also addressed with emphasis on the practical application of the techniques. In total, 376 references in the open literature, dating back to 1971, are compiled to provide an overall picture of historical, current, and future developments in this area.

Keywords: Fault-tolerant control systems (FTCS); Active fault-tolerant control systems (AFTCS); Fault detection and diagnosis (FDD); Reconfigurable control (RC); Bibliographical review

1. Introduction

1.1. Brief historical development and motivation of this paper

Modern technological systems rely on sophisticated control systems to meet increased performance and safety requirements. A conventional feedback control design for a complex system may result in an unsatisfactory performance, or even instability, in the event of malfunctions in actuators, sensors or other system components. To overcome such weaknesses, new approaches to control system design have been developed in order to tolerate component malfunctions while maintaining desirable stability and performance properties. This is particularly important for safety-critical systems, such as aircrafts, spacecrafts, nuclear power plants, and chemical plants processing hazardous materials. In such systems, the consequences of a minor fault in a system component can be catastrophic. Therefore, the demand on reliability, safety and fault tolerance is generally high. It is necessary to design control systems which are capable of tolerating potential faults in these systems in order to improve the reliability and availability while providing a desirable performance. These types of control systems are often known as fault-tolerant control systems (FTCS). More precisely, FTCS are control systems which possess the ability to accommodate component failures *automatically*. They are capable of maintaining overall system stability and acceptable performance in the event of such failures. In other words, a closed-loop control system which can tolerate component malfunctions, while maintaining desirable performance and stability properties is said to be a *fault-tolerant control system.*

Over the last three decades, the growing demand for safety, reliability, maintainability, and survivability in technical systems has drawn significant research in Fault Detection and Diagnosis (FDD). Such efforts have led to the development of many FDD techniques, for example survey papers (Basseville, 1988; Dailly, 1990; Dash & Venkatasubramanian, 2000; Dochain, Marquardt, Won, Malik, & Kinnaert, 2006; Frank, 1990, 1994, 1996; Frank & Ding, 1997; Frank & Koppen-Seliger, 1997a, 1997b; Frank, Ding, & Marcu, 2000; Garcia & Frank, 1997; Gertler, 1988; Gertler, 1993; Gertler, 1997; Isermann, 1984; Isermann, 1993; Isermann, 1997a, 1997b, 2001, 2005; Isermann & Balle, 1997; Isermann, Schwarz, & Stolzl, 2002; Patton, 1991, 1997a; Patton & Chen, 1994; Patton, Chen, & Nielsen, 1995; Sharif & Grosvenor,

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1998; Tzafestas & Watanabe, 1990; Venkatasubramanian, Rengaswamy, Yin, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, Kavuri, & Yin, 2003; Willsky, 1976; Zhong, Fang, & Ye, 2007) and books (Barron, 1996; Basseville & Benveniste, 1986; Basseville & Nikiforov, 1993; Chen & Patton, 1999; Chiang, Russell, & Braatz, 2001; Gertler, 1998; Gustafsson, 2000; Himmelblau, 1978; Isermann, 2006; Mangoubi, 1998; Natke & Cempel, 1997; Patton, Frank, & Clark, 1989, 2000; Pau, 1981; Pouliezos & Stavrakakis, 1994; Romberg, Black, & Ledwidge, 1996; Russell, Chiang, & Braatz, 2000; Simani, Fantuzzi, & Patton, 2003; Vachtsevanos, Lewis, Roemer, Hess, & Wu, 2006; Witczak, 2007). In the literature, fault detection and isolation (FDI) or fault detection and identification (again, FDI) are often used. To avoid any confusion, this paper has adopted FDI to stand for fault detection and isolation, while FDD will be used when the fault identification function is also added to FDI. In FTCS designs, fault identification is important, therefore FDD is mainly used in this paper to highlight the requirement of fault identification. On a parallel path, research on reconfigurable fault-tolerant control systems has increased progressively since the initial research on restructurable control and self-repairing flight control systems began in the early 1980s (Chandler, 1984; Eterno, Weiss, Looze, & Willsky, 1985; Montoya, 1983). An early excellent review on the design issues for fault-tolerant aircraft control was given in 1985 (Eterno et al., 1985). Other early publications of a tutorial nature or demonstrating initial research on this subject include (Chizeck & Willsky, 1978; Montgomery & Caglayan, 1976; Montgomery & Price, 1976; Vander Velde, 1984). More recently, fault-tolerant control has attracted more and more attention in both industry and academic communities due to increased demands for safety, high system performance, productivity and operating efficiency in a wider engineering application, not limited to traditional safety-critical systems. Several review/survey papers on FTCS have appeared since the 1990s (Blanke, Izadi-Zamanabadi, Bogh, & Lunau, 1997; Blanke, Frei, Kraus, Patton, & Staroswiecki, 2000; Blanke, Staroswiecki, & Wu, 2001; Isermann et al., 2002; Jiang, 2005; Patton, 1993, 1997b; Polycarpou & Vemuri, 1998; Rauch, 1994, 1995; Staroswiecki & Gehin, 2001; Steinberg, 2005; Stengel, 1991; Zemlyakov, Rutkovskii, & Silaev, 1996). However, compared to FDI, few books on this subject have been published until recently (Benítez-Pérez & García-Nocetti, 2005; Blanke, Kinnaert, Lunze, & Staroswiecki, 2003, 2006; Hajiyev and Caliskan, 2003; Isermann, 2006; Mahmoud, Jiang, & Zhang, 2003a; Steffen, 2005; Tao, Chen, Joshi, & Tang, 2004). As a milestone, a 2-day workshop on Restructurable Controls was held at NASA Langley Research Center, Hampton, Virginia, USA, September 21–22, 1982 (Montoya, 1983). The first triennial IFAC Symposium on Fault Detection, Supervision and Safety for Technical Process (SAFEPROCESS) was held in 1991 in Baden-Baden, Germany, followed by an IEE Colloquium on Fault Diagnosis and Control System Reconfiguration in 1993 in London, Englend and an International Conference on Fault Diagnosis (TOOLDIAG) in April 1993 in Toulouse, France. Another triennial series of IFAC Workshop on On-Line Fault Detection and Supervision in Chemical Process Industries was first held in 1992 in Newark, USA. More recently, invited tutorial sessions, workshops and plenary talks on these topics have frequently appeared at several major conferences such as AIAA Guidance, Navigation, and Control Conference, American Control Conference, European Control Conference, IEEE Conference on Decision and Control, IFAC World Congress and IFAC SAFEPROCESS. Two special issues on reconfigurable flight control system designs appeared in 1999 (Banda, 1999) and 2005 (Hess, 2005), respectively.

New special issues on fault-tolerant control are to be appeared in different journals.

Historically, from the point of view of practical application, a significant amount of research on fault-tolerant control systems was motivated by aircraft flight control system designs (Steinberg, 2005). The goal, therein, was to provide "self-repairing" capability in order to ensure a safe landing in the event of severe faults in the aircraft (Chandler, 1984; Eterno et al., 1985). Such effort has been stimulated partly by two commercial aircraft accidents in the late 1970s. In the case of Delta Flight 1080 (April 12, 1977) (McMahan, 1978; Montoya, 1983), the elevator became jammed at 19° up and the pilot had been given no indication on this malfunction. Fortunately, the pilot successfully reconfigured the remaining control elements and landed the aircraft safely, based on his experience and knowledge about the actuation redundancy in the L-1011 airplane. In another accident involving American Airlines DC-10 crash in Chicago (Flight 191, May 25, 1979), the pilot had only 15 s to react before the plane crashed. Subsequent investigation showed that the crash could have been avoided (Montoya, 1983). A recent study (Maciejowski & Jones, 2003) provides another evidence for the need of fault-tolerant controls. It shows that the fatal crash of EL AL Flight 1862 of a Boeing 747-200F freighter (October 4, 1992) could have been avoided. These are just three examples of flight accidents which highlight the need for fault-tolerant flight control systems. A system for aiding pilots by providing automatic fault accommodation is therefore highly desirable for both civil and military aircrafts. In safety-critical nuclear power industries, interests in diagnostics and fault-tolerant control of nuclear power plants have been intensified since the Three Mile Island incident (March 28, 1979) and the tragedy at the Chornobyl nuclear power plant on April 26, 1986.

More recently, the fault-tolerant control problem has begun to draw more and more attention in a wider range of industrial and academic communities, due to increased safety and reliability demands beyond what a conventional control system can offer. The applications include aerospace, nuclear power, automotive, manufacturing and other process industries (Bruccoleri, Amico, & Perrone, 2003; Isermann et al., 2002; Mehrabi, Ulsoy, Koren, & Heytler, 2002). Fault tolerance is no longer limited to high-end systems, and consumer products, such as automobiles, increasingly dependent on microelectronic/mechatronic systems, on-board communication networks, and software, thus requiring new techniques for achieving fault tolerance.

Even though individual research on FTCS has been carried out extensively, systematic concepts, design methods, and even terminology are still not yet standardized. Recently, efforts have been made to unify some terminology (Blanke et al., 2000, 2001, 2003, 2006; Isermann, 2006; Isermann & Balle, 1997; Mahmoud et al., 2003a; Simani et al., 2003; Staroswiecki & Gehin, 2001). In addition, due to historical reasons and the complexity of the problem, most of the research on FDD and Reconfigurable Control (RC) was carried out as a two separate entity. More specifically, most of the FDI techniques are developed as a diagnostic or monitoring tool, rather than an integral part of FTCS. As a result, some existing FDD methods may not satisfy the need of controller reconfiguration. On the other hand, most of the research on reconfigurable controls is carried out assuming the availability of a perfect FDD. Little attention has been paid to the analysis and design with the overall system structure and interaction between FDD and RC. For example, from the viewpoint of RC design what are the needs and requirements for FDD? What information can be provided by the existing FDD techniques for overall FTCS designs? How to analyze systematically the interaction between FDD and RC? How to design the FDD and RC in an integrated manner for on-line and real-time applications? Many other challenging issues still remain open for further research and development. One of the motivations of this paper is to provide a bibliographical review on the development in FTCS and to present some challenging open problems for future research. It is our hope that this work can provide some useful information to researchers in the field in order to facilitate further development of this important area.

1.2. Type of fault-tolerant control systems

Generally speaking, FTCS can be classified into two types: *passive* (PFTCS) and *active* (AFTCS). In PFTCS, controllers are fixed and are designed to be robust against a class of presumed faults (Eterno et al., 1985). This approach needs neither FDD schemes nor controller reconfiguration, but it has limited fault-tolerant capabilities. Discussions on PFTCS are beyond the scope of this paper and interested readers are referred to (Hsieh, 2002; Jiang & Zhao, 2000; Liang, Liaw, & Lee, 2000; Liao, Wang, & Yang, 2002; Siljak, 1980; Veillette, 1995; Veillette, Medanic, & Perkins, 1992; Yang, Zhang, Lam, & Wang, 1998a; Yang, Wang, & Soh, 2000; Yang, Yang, & Soh, 2001a; Zhao & Jiang, 1998) and the references therein for recent development. In the literature, PFTCS is also known as *reliable* control systems or control systems with *integrity*.

In contrast to PFTCS, AFTCS react to the system component failures actively by reconfiguring control actions so that the stability and acceptable performance of the entire system can be maintained. In certain circumstances, degraded performance may have to be accepted (Blanke et al., 2001; Patton, 1997b; Stengel, 1991). AFTCS are also referred to as self-repairing (Chandler, 1984; Eterno et al., 1985), reconfigurable (Moerder, Halyo, Broussard, & Caglayan, 1989), restructurable (Looze, Weiss, Eterno, & Barrett, 1985; Montoya, 1983), or self-designing (Monaco, Ward, Barron, & Bird, 1997) control systems by some researchers. From the viewpoint of functionality in handling faults, AFTCS were also named as fault detection, identification (diagnosis) and accommodation schemes by other researchers (Belcastro & Belcastro, 2001; Napolitano, Neppach, Casdorph, & Naylor, 1995a; Polycarpou & Vemuri, 1995; Theilliol, Noura, & Ponsart, 2002; Yen & Ho, 2003). In such control systems, the controller compensates for the impacts of the faults either by selecting a pre-computed control law (Maybeck & Stevens, 1991; Moerder et al., 1989; Rauch, 1995; Zhang & Jiang, 2001a) or by synthesizing a new one on-line (Looze et al., 1985; Patton, 1997b; Zhang & Jiang, 2002a). To achieve a successful control system reconfiguration, both approaches rely heavily on real-time FDD schemes to provide the most up-to-date information about the true status of the system. Therefore, the main goal in a fault-tolerant control system is to design a controller with a suitable structure to achieve stability and satisfactory performance, not only when all control components are functioning normally, but also in cases when there are malfunctions in sensors, actuators, or other system components (e.g. the system itself, control computer hardware or software). This paper focuses only on AFTCS.

1.3. Objectives and structure of AFTCS

The design objectives for AFTCS include the transient and the steady-state performance for the system not only under normal operations, but also under fault conditions. It is important to point out that the emphasis on system behaviors in these two modes of operation can be significantly different. During normal operations, more emphasis should be placed on the quality of the system behavior. In the presence of a fault, however, how the system survives with an acceptable (probably degraded) performance becomes a predominant issue.

Typically, AFTCS can be divided into four sub-systems: (1) a reconfigurable controller, (2) a FDD scheme, (3) a controller reconfiguration mechanism, and (4) a command/reference governor.

Inclusion of both FDD and reconfigurable controllers within the overall system structure is the main feature distinguishing AFTCS from PFTCS. Key issues in AFTCS are how to design: (a) a controller which can be easily reconfigured, (b) a FDD scheme with high sensitivity to faults and robustness to model uncertainties, operating condition variations, and external disturbances, and (c) a reconfiguration mechanism which leads as much as possible to the recovery of the pre-fault system performance in the presence of uncertainties and time-delays in FDD within the constraints of control inputs and system states. The critical issue in any AFTCS is the limited amount of time available for the FDD and for the control system reconfiguration. Furthermore, in case of failure, efficient utilization and management of redundancy (in hardware, software and communication networks), stability, transient and a steady-state performance guarantee are some of the important issues to consider in AFTCS.

An overall structure of a typical AFTCS is shown in Fig. 1. In the FDD module, any fault in the system should be detected and isolated as quickly as possible, and fault

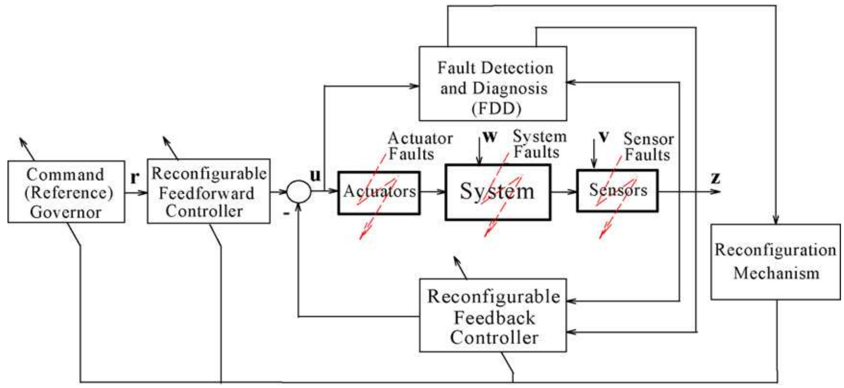

Fig. 1. A general structure of AFTCS.

parameters, system state/output variables, and post-fault system models need to be estimated on-line in real-time. Based on the on-line information on the post-fault system model, the reconfigurable controller should be designed automatically to maintain stability, desired dynamic performance and steady-state performance. In addition, in order to ensure the closed-loop system to track a command input trajectory in the event of faults, a reconfigurable feedforward controller often needs to be synthesized. To avoid potential actuator saturation and to take into consideration the degraded performance after fault occurrence, in addition to a reconfigurable controller, a command/reference governor may also need to be designed to adjust command input or reference trajectory automatically.

Based on the above structure, the design objectives of AFTCS can be stated as to (1) have a FDD scheme to provide as precisely as possible, the information about a fault (time, type and magnitude) and the post-fault model, and (2) design a new control scheme (reconfig-urable/restructurable) to compensate the fault-induced changes in the system so that the stability and acceptable closed-loop system performance can be maintained. Furthermore, it is important to point out that not only the parameters of the controllers need to be recalculated, but also the structure of the new controllers (in terms of the order of the controllers, the numbers and the types of the controllers) might be changed. The corresponding AFTCS are often referred to as *restructurable* control systems (Stengel, 1991; Patton, 1997b; Zhang & Jiang, 2002b) to emphasize the controller structure change. Note that, in the literature, there are generally two classifications on AFTCS. One classifies the AFTCS as reconfigurable versus restructurable; the other differentiates them as accommodation versus reconfiguration (Blanke et al., 2000, 2003, 2006). In this paper, we adopt the former. So long as there is no confusion, we will use the term "reconfigurable control" in subsequent sections.

The paper is organized as follows: In Section 2, review and classification of existing reconfigurable control techniques are provided. A brief review on existing FDD methods is given in Section 3. Current research relating AFTCS are outlined in Section 4 followed by conclusions in Section 5. More than 300 papers as well as some useful web sites in the open literature from 1971 to date are collected as the references.

2. Classification of existing reconfigurable control techniques

2.1. Classification based on control algorithms

In the literature, the existing reconfigurable control design methods fall into one of the following approaches: linear quadratic; pseudo-inverse/control mixer; gain scheduling/linear parameter varying; (model reference) adaptive control/model following; eigenstructure assignment; multiple-model; feedback linearization or dynamic inversion; Hoo and other robust controls; model predictive control; variable structure and sliding mode control; generalized internal model control; and intelligent control using expert systems, neural networks, fuzzy logic and learning methodologies. Detailed classification can be carried out according to the following criteria (1) mathematical design tools; (2) design approaches; (3) reconfiguration mechanisms; and (4) type of systems to be dealt with. Such a classification is shown in Fig. 2. Furthermore, a list of existing control approaches with corresponding references is provided in Table 1.

The control algorithms for FTCS in Table 1 and Fig. 2 have been listed roughly in chronological order to highlight the historical evolution of fault-tolerant control design techniques. In addition, many reconfigurable control design methods rely on those ideas that had been investigated in the past for other control purposes. Even though well-known control design methods have been used, it poses new problems and challenges that may not appear in the conventional controller designs. An important criterion for judging the suitability of a control method for AFTCS is its ability to be implemented to maintain an acceptable (nominal or degraded) performance in the impaired system in an *on-line* real-time setting. In this regard, the following requirements should be satisfied:

- control reconfiguration must be done under real-time constraints;
- the reconfigurable controller should be designed automatically with little trail-and-error and human interactions; and
- the methods selected must provide a solution even if the solution is not optimal.

- Classification of FTC methods
  - Mathematical design tools
    - Linear Quadratic (LQ)
    - Pseudo-Inverse (PI)
    - Intelligent Control (IC)
    - Gain Scheduling (GS)/Linear Parameter Varying (LPV)
    - Model Following (MF)
    - Adaptive Control (AC)
    - Multiple Model (MM)
    - Eigenstructure Assignment (EA)
    - Feedback Linearization (FL)/Dynamic Inversion (DI)
    - H_∞ and other robust control techniques
    - Model Predictive Control (MPC)
    - Quantitative Feedback Theory (QFT)
    - Linear Matrix Inequality (LMI)
    - Variable Structure Control (VSC)/Sliding Mode Control (SMC)
    - Generalized Internal Model Control (GIMC)
  - Design approaches
    - Pre-computed control laws
      - MM
      - GS/LPV
      - QFT
      - LMI
      - GIMC
    - On-line automatic redesign
      - LQ
      - PI
      - MF/AC
      - EA
      - FL/DI
      - VSC/SMC
      - MPC
  - Reconfiguration mechanisms
    - Optimization
      - LQ
      - H_∞/μ synthesis
      - LMI
      - MPC
    - Switching
      - MM
      - GS/LPV
      - VSC/SMC
    - Matching
      - PI—System matrix
      - EA—Eigenstructure
    - Following
      - MF—State/Output
      - MPC—Set-point/Output
    - Compensation
      - Additive compensation
      - Adaptive compensation
  - Type of Systems dealt with
    - Linear systems: LQ; PI; MF; EA; MM; MPC; QFT; GIMC
    - Nonlinear systems: GS/LPV; MM; FL/DI; LMI; VSC/SMC; IC

Fig. 2. Classification of AFTCS.

- Control Structures
  - Adaptive
    - Indirect
    - Direct
  - Switching
    - GS/LPV
    - MM
    - VSC/SMC
  - Following
    - Explicit MF
    - Implicit MF

$\underset{Combination}{\overset{Interaction}{\Longleftrightarrow}}$

- Control Algorithms
  - Optimization
    - LQ
    - H_∞
    - LMI
    - MPC
  - Matching
    - EA
  - Inversion
    - PI
    - DI

Fig. 3. Combination of reconfigurable control algorithms in AFTCS.

Table 1
Existing control design methodologies in AFTCS.

Design approaches	References
Linear quadratic	Looze et al. (1985), Joshi (1987), Moerder et al. (1989), Huang and Stengel (1990), Ahmed-Zaid, Ioannou, Gousman, and Rooney (1991), McLean and Aslam-Mir (1994), Veillette (1995) and Yang et al. (2000)
Pseudo-inverse	Rattan (1985), Caglayan, Allen, and Wehmuller (1988), Gao and Antsaklis (1991), Yang and Blanke (2000), Bajpai, Chang, and Lau (2001) and Hajiyev and Caliskan (2001)
Intelligent control	Handelman and Stengel (1989), Farrell, Berger, and Appleby (1993), Kwong, Passino, Laukonen, and Yurkovich (1995), Napolitano et al. (1995b), Polycarpou and Vemuri (1995), Polycarpou and Helmicki (1995), Reveliotis and Kokar (1995), Liu (1996), Schram and Verbruggen (1998), Balle et al. (1998), Wang and Wang (1999), Lopez-Toribio, Patton, and Daley (2000), Napolitano et al. (2000), Diao and Passino (2001), Diao and Passino (2002), Holmes and Ray (2001), Demetriou and Polycarpou (2001), Polycarpou (2001), Ho and Yen (2002) and Ichtev (2003)
Gain scheduling/LPV	Moerder et al. (1989), Bennani, van der Sluis, Schram, and Mulder (1999), Ganguli, Marcos, and Balas (2002) and Shin et al. (2004)
Model following	Huang and Stengel (1990), Morse and Ossman (1990), Gao and Antsaklis (1992), Dhayagude and Gao (1996), Bodson and Groszkiewicz (1997), Zhang and Jiang (2002a) and Kim, Lee, and Kim (2003)
Adaptive control	Ahmed-Zaid et al. (1991), Bodson and Groszkiewicz (1997), Wise et al. (1999), Tao, Joshi, and Ma (2001), Tao, Chen, and Joshi (2002) and Kim et al. (2003)
Multiple-model	Maybeck and Stevens (1991), Napolitano and Swaim (1991a), Rauch (1995), Maybeck (1999), Boskovic and Mehra (2000), Zhang and Jiang (2001a), Boskovic and Mehra (2002) and Yen and Ho (2003))
Integrated diagnostics and control	Jacobson and Nett (1991), Hwang et al. (1994), Stoustrup et al. (1997), Musgrave, Guo, Wong, and Duyar (1997), Balle et al. (1998), Katebi and Grimble (1999), Hajiyev and Caliskan (2001) and Zhang and Jiang (2001a, 2001b, 2002a)
Eigenstructure assignment	Napolitano and Swaim (1991b), Jiang (1994a), Zhao and Jiang (1998), Konstantopoulos and Antsaklis (1999) and Zhang and Jiang (2001a, 2002a)
Feedback linearization/DI	Ochi and Kanai (1991), Ochi (1993), Ochi and Kanai (1995), Wise et al. (1999), Bacon et al. (2001), Calise et al. (2001) and Doman and Ngo (2002)
H_∞ robust control	Veillette et al. (1992), Wu and Chen (1996), Wu (1997), Yang, Lam, and Wang (1998), Yang and Stoustrup (2000) and Yang, Wang, and Soh (2001b)
Model predictive control	Pachter et al. (1995), Monaco et al. (1997), Huzmezan and Maciejowski (1998), Maciejowski (1999) and Kale and Chipperfield (2005)
Quantitative feedback theory	Keating, Pachter, and Houpis, 1997, Wu, Grimble, and Wei (2000a), Siwakosit and Hess (2001) and Niksefat and Sepehri (2002)
Linear matrix inequality	Wise and Sedwick (1998), Chen et al. (1999), van der Sluis et al. (2000), Demetriou (2001), Ganguli et al. (2002) and Liao et al. (2002)
Variable structure control/SMC	Shtessel et al. (1999), Shtessel et al. (2002), Kim and Kim (2000), Kim et al. (2001) and Hess and Wells (2003)
Generalized internal model control	Zhou and Ren (2001) and Campos-Delgado and Zhou (2003)
Overall architecture and others	Blanke et al. (1997), Wills et al. (2001) and Puig and Quevedo (2001)

Although each individual control design method has been summarized in Fig. 2 and Table 1, in practice, a combination of several methods may be more appropriate to achieve the best overall FTCS. In this regard, hardly any reconfigurable control technique relies on a single control design technique, rather it uses a combination of different control structures and control design algorithms. This can be shown in Fig. 3. A list of existing publications based on the combination of different controller structures and design algorithms is provided in Table 2.

2.2. Classification based on field of applications

A list of publications in some application-oriented research is summarized in Table 3. As it can be seen, a large amount of research has been carried out in the framework of aircraft flight control. Several reconfigurable flight control systems have been flight tested (Anonymous, 2007a; Brinker & Wise, 2001; Corvin et al., 1991; Monaco et al., 1997; Page, Monaco, & Meloney, 2006; Shore & Bodson, 2005).

With rapid advances in microelectronics, mechatronics, smart actuator and sensor techniques, and computing technologies, and motivated by increased demands for high requirements on system performance, product quality, productivity and operating efficiency beyond the conventional safety-critical aerospace and nuclear power systems, FTCS design is becoming an important feature to be considered in commercial product development and system design such as drive-by-wire automobiles (Isermann et al., 2002), manufacturing (Mehrabi et al., 2002) and other industrial systems (Antaki, Paden, Piovoso, & Banda, 2002; Goodall & Kortum, 2002). Recently, concepts and methodologies developed in the fly-by-wire (FBW) fault-tolerant flight control systems having been extended to a wide range of engineering systems such as automobiles, railway vehicles, surface ships, autonomous underwater vehicles, automated highway systems (petro)chemical plants, power systems, robots, medical systems and other industrial systems. Furthermore, to show the historical and current research activities on FTCS, several research programs and benchmarks on reconfigurable (fault-tolerant) control systems are presented in Table 4.

Table 2
Methods based on combination of different approaches.

Design approaches	References
Adaptive control	
With LQ	Ahmed-Zaid et al. (1991)
With model following	Bodson and Groszkiewicz (1997) and Kim et al. (2003)
With fuzzy/neural control	Napolitano et al. (2000), Calise et al. (2001) and Diao and Passino (2001)
GS/LPV	
With LQG	Moerder et al. (1989)
With MPC	Huzmezan and Maciejowski (1998)
With LMI	van der Sluis et al. (2000), Ganguli et al. (2002) and Shin, Wu, and Belcastro (2002)
With μ synthesis	Bennani et al. (1999)
With EA	van der Sluis et al. (2000)
Multiple-model	
With LQG	Maybeck and Stevens (1991)
With EA	Zhang and Jiang (2001a)
With MPC	Kanev and Verhaegan (2000) and Ichtev (2003)
With fuzzy logic	Schram and Verbruggen (1998), Lopez-Toribio et al. (2000), Diao and Passino (2002) and Ichtev, 2003
With neural network	Diao and Passino (2002)
VSC/SMC	
With model following	Kim and Kim (2000)
Model following	
With LQ	Huang and Stengel (1990)
With dynamic inversion	Wise et al. (1999), Bacon et al. (2001) and Brinker and Wise (2001)
With EA and command governor	Zhang and Jiang (2003)

Table 3
Classification of AFTCS according to field of applications.

Applications	References
Aircraft/helicopters	Looze et al. (1985), Ostroff (1985), Moerder et al. (1989), Huang and Stengel (1990), Monaco et al. (1997), Heiges (1997), Ward et al. (1998), Huang, Celi, and Shih (1999), Wise et al. (1999), Napolitano et al. (2000), Brinker and Wise (2001), Elgersma and Glavaski (2001), Zhang and Jiang (2001a, 2002a), Antaki et al. (2002), Enns and Si (2003), Hess and Wells (2003), Kim et al. (2003), Pachter and Huang (2003), Boskovic, Bergstrom, and Mehra (2005) and Boskovic, Prasanth, and Mehra (2007)
Spacecraft and structures	Yen (1994), Musgrave et al. (1997) and Blanke et al. (1997)
Automotive and highway systems	Kim, Rizzoni, and Utkin 1998), Kim et al. (2001), Isermann et al. (2002), Lygeros et al. (2000) and Spooner and Passino (1997)
Surface/underwater marine vehicles	Payton, Keirsey, Kimble, Krozel, and Rosenblatt (1992), Rauch (1995), Katebi and Grimble (1999), Mort and Derradji (1999), Yang, Yuh, and Choi (1999), Caccia and Veruggio (2000), Blanke (2001), Podder et al. (2001a), Podder et al. (2001b), Wills et al. (2001), Sarkar et al. (2002), Antonelli (2003), Omerdic, Roberts, and Vukic (2003) and Zivi (2005)
Engine and propulsion control	Blanke, Izadi-Zamanabadi, and Lootsma (1998), Izadi-Zamanabadi and Blanke (1999), Jonckheere, Lohsoonthorn, and Bohacek, 1999, Diao and Passino (2001) and Bonivento, Paoli, and Marconi (2003)
(Nuclear) power systems	Ray (1985), Chung and Chang (1986), Carcia, Ray, and Edwards (1991), Carcia et al. (1995) and Eryurek and Upadhyaya (1995)
Chemical/petrochemical plants	Martini, Chylla, and Cinar (1987), Zhou & Frank (1998) and Prakash, Patwardhan, & Narasimhan (2002)
Robots	Kimura, Takahashi, Okuyama, Tsuchiya, & Suzuki (1998), Groom, Maciejewski, & Balakrishnan (1999), Shin & Lee (1999), Liu (2001) and Ji, Zhang, Biswas, & Sarkar (2003)
Other engineering systems	
Buildings and air-conditioning systems	Liu & Dexter (2001), Wang & Chen (2002) and Xie, Zhou, Jin, & Liu (2002)
Industrial furnaces and heat exchanger	Balle et al., 1998, Gopinathan, Mehra, & Runkle (2000)
Drug infusion	Barros and des Santos (1998)
Motors and drives	Hwang et al., 1994, Bennett, Patton, & Daley (1999), Lopez-Toribio et al., 2000, Bolognani, Zordan, & Zigliotto (2000), Bianchi, Bolognani, Zigliotto, & Zordan (2003) and Sepe, Morrison, & Miller (2003)
Networks	Provan & Chen (2001)
Paper machines	Kabore & Wang (2001)
Rotor/magnetic bearing systems	Cole, Keogh, & Burrows (2000)
Water-tank systems	Noura, Sauter, Hamelin, & Theilliol (2000b), Theilliol et al., 2002 and Yen & Ho (2003)
Winding machines	Noura et al. (2000b)

Table 4
Research programs and benchmarks on fault-tolerant control.

Applications	Sponsors or organizations
Research programs in flight control area:	
Self-repairing flight control systems	Sponsored by Air Force Research Lab, WPAFB, OH (1984–1990) (Chandler, 1984; Eslinger & Chandler, 1988)
Automatic redesign for restructurable control systems	Sponsored by NASA Langley and carried out by Alphatech (1984–1987) (Looze et al., 1985)
Self-designing flight control	Sponsored by Air Force Office of Scientific Research and carried out by Barron Associates, Inc. for VISTA/F-16 aircarft (1993–1996) (Monaco et al., 1997; Ward, Barron, Carley, & Curtis, 1994; Ward & Barron, 1995; Ward et al., 1998)
Reconfigurable control for tailless aircraft (RESTORE)	Sponsored by Air Force Research Labs, WPAFB, OH for the NASA/Boeing X-36 Tailless Aircraft (1989–1996–2000) (Brinker and Wise, 2001; Wise et al., 1999)
ACTIVE (advanced control technology for integrated vehicles) and IFCS (intelligent flight control system)	Sponsored by NASA Dryden Flight Research Center (ACTIVE: 1996-1999; IFCS: 1999–2004) (Anonymous, 2007b)
Aircraft prognostics and health management, and adaptive reconfigurable control	Sponsored by NASA Dryden's Small Business Innovation Research (SBIR) program and carried out by Scientific Systems Co., Inc. (Boskovic and Mehra, 2002)
Reconfigurable control for active management of aircraft system failures (AMASF)	Sponsored by NASA Langley Research Center and carried oou by Honeywell Lab. (Elgersma and Glavaski, 2001)
Aviation safety program (AvSP)–single aircraft accident prevention (SAAP)	Sponsored by NASA Aviation Safety Program Office (Belcastro and Belcastro, 2001)
An open platform for reconfigurable control	Sponsored by DARPA Software-Enabled Control program and carried out by Georgia Tech (Wills et al., 2001)
Fault-tolerant control	Sponsored by GARTEUR (Group for Aeronautical Research and Technology in EURope), 2004–2007 (Anonymous, 2007c; Smaili, Breeman, Lombaerts, and Joosten (2006))
Other benchmarks and projects	
Ship propulsion system	Proposed by Aalborg University under the European Science Foundation COSY project (1996–1999) (Izadi-Zamanabadi & Blanke, 1999; Izadi-Zamanabadi et al., 2001)
Three-tank system	Proposed by Ruhr University Bochum under the European Science Foundation COSY project (1996–1999) (Lunze et al., 2001)
IFATIS (intelligent fault-tolerant control in integrated systems)	Funded by the European Commission in the Information Society Technologies (IST) programme (2002–2004) (Koppen-Seliger, Ding, & Frank, 2002)
NeCST (networked control systems tolerant to faults)	Funded by the European Commission in the Information Society Technologies (IST) programme (2004–2007) (Anonymous, 2007d)

3. Classification of existing FDD approaches

As mentioned previously, a lot of work has been done in the area of FDD in the last three decades. Many FDD schemes have been developed. Among many excellent survey papers from control engineering point of view (Basseville, 1988; Dailly, 1990; Dochain et al., 2006; Frank, 1990, 1994, 1996; Frank & Ding, 1997; Frank & Koppen-Seliger, 1997a, 1997b; Frank et al., 2000; Garcia & Frank, 1997; Gertler, 1988, 1993, 1997; Isermann, 1984, 1993, 1997a, 1997b, 2001, 2005; Isermann & Balle, 1997; Isermann et al., 2002; Mehra & Peschon, 1971; Patton, 1991, 1997a; Patton & Chen, 1994; Patton et al., 1995; Tzafestas & Watanabe, 1990; Willsky, 1976), most recently, a comprehensive review on the development of process FDD have appeared in a series of papers including three parts (Venkatasubramanian, Rengaswamy, Yin, et al., 2003; Venkatasubramanian, Rengaswamy, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, Kavuri, et al., 2003). There, the authors have presented a comprehensive coverage of FDD approaches developed with more emphasis on research activities in (petro)chemical process industries. The quantitative model-based, qualitative model-based, and process history-based methods have been reviewed in each of the three parts. However, majority of research in FDD area is still for monitoring or diagnostics purposes, rather for control applications. There are relatively few results on the systematic study about the role of FDD in the overall framework of AFTCS and information about the way/methodology to design FDD for reconfigurable control in the context of AFTCS (Patton, 1997b). Preliminary researches in Jiang (1994b), Jia and Jiang (1994), Patton (1997b) and Jiang and Zhao (1997) have demonstrated that the state estimation based schemes are most suitable for fault detection since they are inherently fast and cause a very short time delay in the real-time decision-making process in comparison with parameter estimation approach. However, the information from the state estimation based algorithms may not be detailed enough for subsequent control system reconfiguration since fault-induced changes in parameters or even system model need to be determined. Parameter

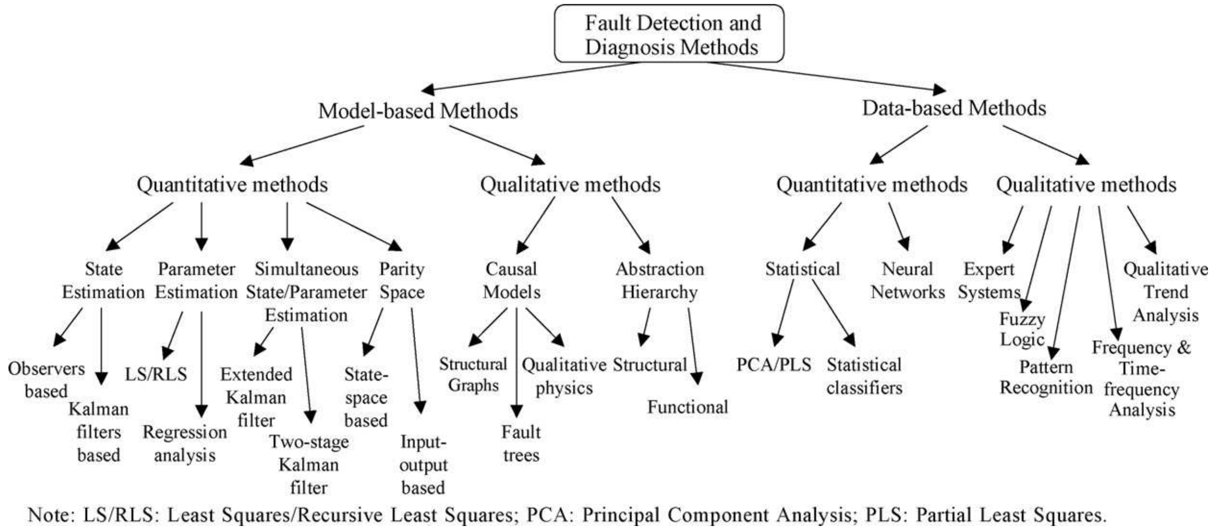

Fig. 4. Classification of FDD methods.

estimation based schemes are more desirable in this regard. Consequently, a combination of the state and the parameter estimation based schemes is probably more appropriate (Patton, 1997b; Wu, Grimble, & Wei, 2000b; Zhang & Jiang, 2002a). In fact, there is a tendency to use parameter estimation techniques for reconfigurable flight control systems (Buffington, Chandler, & Pachter, 1999; Chandler, Pachter, & Mears, 1995; Napolitano, Song, & Seanor, 2001; Song, Campa, Napolitano, Seanor, & Perhinschi, 2002; Ward, Monaco, & Bodson, 1998). Therefore, discussion on the FDD techniques in this paper will mainly be focused on those that can be incorporated into AFTCS. For more comprehensive examination of the subject on FDD, readers are referred to the following survey papers (Basseville, 1988; Dailly, 1990; Dash & Venkatasubramanian, 2000; Dochain et al., 2006; Frank, 1990, 1994, 1996; Frank & Ding, 1997; Frank et al., 2000; Garcia & Frank, 1997; Gertler, 1988, 1993, 1997; Isermann, 1984, 1993, 1997a, 1997b, 2001; Isermann & Balle, 1997; Isermann et al., 2002; Patton, 1991, 1997a; Patton & Chen, 1994; Patton et al., 1995; Sharif & Grosvenor, 1998; Venkatasubramanian, Rengaswamy, Yin, et al., 2003; Venkatasubramanian, Rengaswamy, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, Kavuri, et al., 2003; Willsky, 1976) and books (Barron, 1996; Basseville & Benveniste, 1986; Basseville & Nikiforov, 1993; Chen & Patton, 1999; Chiang et al., 2001; Gertler, 1998; Gustafsson, 2000; Himmelblau, 1978; Isermann, 2006; Mangoubi, 1998; Patton et al., 1989; Patton et al., 2000; Pau, 1981; Pouliezos & Stavrakakis, 1994; Romberg et al., 1996; Russell et al., 2000; Simani et al., 2003; Witczak, 2007).

As it is well-known, an FDD scheme has three tasks: (1) *fault detection* indicates that something is wrong in the system, i.e., the occurrence of a fault and the time of the fault occurrence; (2) *fault isolation* determines the location and the type of the fault (which component has failed); and (3) *fault identification* determines the magnitude (size) of the fault. Fault isolation and identification are usually referred to as *fault diagnosis* in the literature (Isermann, 1997a). Based on the above classification, FDD often represent the functions including both fault detection and diagnosis, or simply called fault diagnosis (Isermann, 2006).

In the following sections, a classification of existing FDD approaches is given first, followed by a classification based on *residual generation* and *residual evaluation* for model-based approaches. Comparison of various FDD approaches is then provided using several criteria.

3.1. Classification based on dependence on the system

The existing FDD approaches can be generally classified into two categories: (1) model-based and (2) data-based (model-free) schemes; these two schemes can further be classified as quantitative and qualitative approaches. Essentially, a quantitative model-based FDD scheme utilizes mathematical model (often known as analytical redundancy) to carry out FDD in real-time. Four most commonly used techniques are based on (1) state estimation; (2) parameter estimation; (3) parity space; and (4) combination of the first three. Based on the classification in (Venkatasubramanian, Rengaswamy, Yin, et al., 2003), a refined classification of the existing FDD approaches is shown in Fig. 4.

Since most of control techniques are model-based, fault-tolerant controllers need to be designed based on the mathematical model of the system being analyzed, particularly the post-fault model of the system. Our focus, hereafter, will mainly be on those FDD approaches relying on quantitative models. Readers interested in other approaches are referred to recent review papers (Frank et al., 2000; Isermann, 2005; Venkatasubramanian, Rengaswamy, Yin, et al., 2003; Venkatasubramanian, Rengaswamy, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, Kavuri, et al., 2003) and books (Chiang et al., 2001; Isermann, 2006; Russell et al., 2000; Vachtsevanos et al., 2006; Witczak, 2007) for detail.

- Classification according to residual generation techniques in model-based approaches.
  - State Estimation
    - Observers
      - Observer, excited by one output
      - Bank of observers
      - Unknown Input Observer (UIO)
    - Kalman filters
      - Kalman filter, excited by all outputs
      - Multiple-model filters
      - Fault detection filters
  - Parameter Estimation
    - Least-squares (LS) or recursive least-squares (RLS)
    - Regression analysis
    - Bounding parameter estimation
  - Simultaneous/Joint State & Parameter Estimation
    - Adaptive observers
    - Extended Kalman filter (EKF)
    - Two-stage Kalman filter
    - Two-level (two-step) estimation
  - Parity Space
    - State-space-based methods
    - Input-output-based methods
- Classification according to residual evaluation criteria.
  - Threshold test on instantaneous or moving averagevalues of the residuals
  - Statistical methods
    - Hypothesis tests on mean, covariance and whiteness
    - Weighted sum-squared residual (WSSR) test
    - Sequential probability ratio test (SPRT)
    - Cumulative sum (CUSUM)
    - Generalized likelihood ratio (GLR) test
    - Multiple hypothesis test (MHT)
    - Multi-level hypotheses test
  - Methods based on fuzzy logic symptom evaluation
  - Methods based on neural network pattern classification

In order to evaluate the suitability of FDD for AFTCS, it is desirable to identify a set of features associated with different FDD approaches. In this regard, the following criteria have been used in this paper: (1) ability to handle different type of faults (actuator, sensor, and component faults); (2) ability to provide quick detection; (3) isolability; (4) identifiability; (5) suitability for FTC; (6) identifiability for multiple faults; (7) suitability to nonlinear systems; (8) robustness to noise and uncertainties; and (9) computational complexity.

Features of the existing quantitative model-based approaches are summarized in Table 5.

A quick glance at the existing methods reveals that none of the single method to satisfies all the criteria. Parameter estimation, simultaneous state and parameter estimation, and multiple-model based approaches are more suitable to the framework of overall AFTCS.

3.2. Classification based on applications

Most applications of model-based diagnostic systems have so far been on aerospace, electrical and mechanical systems, while the data-driven diagnostic techniques have been dominated in the applications to (petro)chemical systems since the unavailability/complexity of high fidelity models and the inherent nonlinear nature of processes. A comprehensive list of the developed FDD techniques for diverse range of engineering applications up to 1996 has been provided in (Isermann & Balle, 1997). New application examples can also be found in (Blanke et al., 2003, 2006; Chiang et al., 2001; Isermann, 2001; Isermann et al., 2002; Simani et al., 2003; Venkatasubramanian, Rengaswamy, Yin, et al., 2003; Venkatasubramanian, Rengaswamy, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, Kavuri, et al., 2003). The current paper will not attempt to perform such a classification in the interest of space.

4. Current research in AFTCS

Since the nature and severity of faults are generally unknown *a priori*, neither does the post-fault system dynamics, FDD schemes have to be used to construct the post-fault system

Table 5
Features of various FDD methods.

Criteria\method	State estimation				Parameter estimation RLS and variants	Simultaneous state and parameter estimation		Parity space
	Single		Multiple					
	Observer	Kalman filter	Observers	Kalman filter		Extended Kalman filter	Two-stage Kalman filter	
Fault sensor	√	√	√	√	*	√	√	√
Actuator	+	+	+	√	√	√	√	+
Type structure	+	+	+	√	√	√	√	+
Speed of detection	√	√	√	√	*	√	√	√
Isolability	×	×	√	√	√	√	√	√
Identifiability	×	×	+	*	√	√	√	*
Suitability for ftc	×	×	√	√	√	√	√	×
Multiple faults identifiability	–	–	√	√	√	√	√	*
Nonlinear systems	×	×	+	√	+	√	√	√
Robustness	–	–	*	*	+	+	+	√
Computational complexity	√	√	*	*	√	*	√	√

Note: (√) favorable; (*) less favorable; (×) not favorable; (+) applicable; (–) not applicable.

model for AFTCS design. The performance of the overall system will depend on many factors, such as the speed and the accuracy of the FDD scheme, the availability of the remaining healthy (functional) actuators, the strategy to utilize hardware/analytical redundancy in the system, the type of control strategies adopted in the reconfigurable controller design, and the integration of these components to form an overall AFTCS. Due to real-time requirements and the dynamic nature of the system, there is usually only a very limited amount of time available to carry out the post-fault model construction and control reconfiguration actions. The trade-off among various design objectives and interaction among different subsystems have to be carried out on-line in real-time. These issues are associated with modelling, stability, performance, robustness, nonlinearity, simulation, implementation and applications. However, for AFTCS, there are several additional challenges beyond those in the conventional control systems, such as redundancy management, integration of FDD and reconfigurable controller, safety and reliability design targets. Overall, some of the current research interests are identified and listed briefly as follows and will be discussed in more detail in the subsequent sections. Note that no attempt has been made to compile an exhaustive list.

- Redundancy:
  - o Hardware versus analytical redundancy.
  - o Dynamic redundancy management.
  - o Control action re-allocation and re-distribution.
- Modelling:
  - o On-line model identification of closed-loop systems for reconfigurable control.
- Stability:
  - o Stability analysis, stability-guaranteed design, and stability robustness.
- Performance:
  - o Design for graceful performance degradation.
  - o Transient/Transition management techniques.
- Uncertainty and robustness:
  - o Coping with FDD uncertainties and reconfiguration delay, and performance robustness.
- Nonlinearity:
  - o Applications to nonlinear systems.
  - o Dealing with constraints in control input (actuator saturation) and system state/output.
- Integration:
  - o Integrated design of FDD and reconfigurable/restructurable control.
  - o Integration of passive and active FTCS.
  - o Integration of intelligent actuator and sensor techniques in AFTCS.
  - o Integration of signal processing, control, communication and computing technologies in the implementation of AFTCS.
- Safety and reliability:
  - o Analysis and assessment for safety and reliability.
- Implementations and applications:
  - o Real-time issues and networked control system applications.
  - o Electronic/mechatronic hardware versus software integration/implementation.
  - o Verification and certification.
- New development:
  - o Novel system architectures, design approaches, and applications.

4.1. Hardware versus analytical (software) redundancy

Redundancy is the key ingredient in any fault-tolerant system. For example, almost all modern military aircrafts and the new generation of civil aircrafts such as Boeing 777 and Airbus A320/330/340/380 have triplex- or quadruplex-redundant actuation systems, flight control computers and databus systems, air data and motion sensor systems (Bartley, 2001; Briere, Favre, & Traverse, 2001). Such redundancies are implemented in both hardware and software.

Since the late 1970s, with the development of fly-by-wire flight control systems, the flight control computer becomes a critical component in automated flight control systems. This motivated the development of the concept of "analytical redundancy" which uses signals generated from a mathematical model of the system for fault detection, diagnosis and accommodation. It is this analytical redundancy that leads to significant research and development in FTCS. In fact, reconfigurable/fault-tolerant control introduces a new view to redundancy, where reliability is achieved through software rather than strictly hardware. Through the use of analytical redundancy, it is possible to reduce the dependence on hardware redundancies (Patton, 1993; Isermann et al., 2002). However, cautions must be paid for how to efficiently and effectively utilize the analytical redundancy (Osder, 1999; Hammett, 1999). This introduces challenging issues for AFTCS design regarding (1) the overall fault-tolerant and redundant system architecture; (2) optimal configuration of hardware and software redundancy by trading-off reliability specifications against the cost; and (3) how to design and implement a fault-tolerant controller to best utilize both types of redundancies in order to achieve design objectives. Quantitative measures of the degree of redundancy are also important considerations for research (Jiang & Zhao, 2000; Wu & Klir, 2000; Zhao & Jiang, 1998).

4.2. Integrated design of FDD and reconfigurable control

To build a functional AFTCS, it is important to examine all subsystems closely to ensure that they can work in harmony. To be more precise, from a reconfigurable control viewpoint, one needs to examine the kind of information needed from a FDD to achieve a reasonable control strategy, and from a FDD standpoint, one needs to know what information can be generated. The demand and supply between these two subsystems should match adequately, otherwise, the overall system may not function as expected. An incorrect or excessively delayed FDD decision may not only result in loss of performance, but also instability for the overall system. A reconfigurable control mechanism based on incorrect fault information will certainly lead to undesirable behavior. A seamless integration of a FDD scheme and appropriate reconfigurable control techniques still poses significant challenges in practice, and deserve further investigation (Zhang & Jiang, 2006). As pointed out also in (Morari & Lee, 1999), integration of performance monitoring and diagnosis with model predictive controllers for industrial applications remains one of the future research topics.

Efforts have been made to combine different subsystems of AFTCS to form an integrated design approach and to evaluate the performance of the overall AFTCS (Hwang, Peng, & Hsu, 1994; Jiang, 1994b; Tsui, 1994; Kobi, Nowakowski, & Ragot, 1994) (Balle, Fischera, Fussel, Nells, & Isermann, 1998; Campos-Delgado, Martinez Martinez, & Zhou, 2005; Eberhardt & Ward, 1999; Eryurek & Upadhyaya, 1995; Hajiyev & Caliskan, 2001; Huang, Reklaitis, & Venkatasubramanian, 2000, 2002; Jiang & Chowdhury, 2005; Katebi & Grimble, 1999; Kim, Rizzoni, & Utkin, 2001; Liu, Wang, & Li, 2004; Noura, Theilliol, & Sauter, 2000a; Shin, Wu, & Belcastro, 2004; Wise et al., 1999; Zhang & Jiang, 2001b; Zhang & Jiang, 2001a, 2002a). Following a different design philosophy, an integrated control and diagnosis method is developed in (Jacobson & Nett, 1991) using a four-parameter (four-degree-of-freedom) controller. Further development in this direction can be found in (Marcos & Balas, 2005; Murad, Postlethwaite, & Gu, 1996; Niemann & Stoustrup, 1997; Stoustrup, Grimble, & Niemann, 1997; Tyler & Morari, 1994). Using the well-known Youla parameterization controller architecture, new fault-tolerant control systems were proposed and analyzed recently in (Campos-Delgado & Zhou, 2003; Marcos & Balas, 2005; Stoustrup & Niemann, 2001; Zhou & Ren, 2001). In addition, the connection between the four-parameter parameterization and Youla parameterization has been established in (Tyler & Morari, 1994). To balance the performance between control and diagnostic functions, a mixed H_2/H_∞ criterion has been used to design a FTCS with optimized control and diagnostic performance indexes in (Wu, 1997).

Merging different subsystems in FTCS seems to be a straightforward task in principle, unfortunately, this is never the case in reality. The main difficulty lies in the fact that each individual subsystem, although operating perfectly on its own, is difficult to provide decisions/actions instantaneously for other subsystems. How to integrate them effectively for practical applications still remains an important topic for further research. How to mitigate the adverse interactions between each subsystem is an important issue worth investigating (Eberhardt & Ward, 1999). How to balance the robustness of the performance during the system normal operation versus the fault sensitivity at the time of a system component failure is also an important issue to be considered (Wu & Chen, 1996; Wu, 1997). For further discussion about issues on integration of FDD and reconfigurable control in AFTCS, interested readers are referred to a recent survey paper (Zhang & Jiang, 2006).

4.3. Design for graceful performance degradation

In any FTCS design, one of the important issues is to consider whether to attempt to recover the original system performance after occurrence of a fault or to accept some degree of performance degradation. What are the consequences if the performance degradation is not taken into consideration and how to take such performance degradation into account in the design process? Such important issues have not been well-studied (Blanke et al., 2001; Jiang & Zhang, 2006; Patton, 1997b; Zhang & Jiang, 2003) so far. In practice, in the case of a sensor fault, the original system performance could be recovered as long as the correct information is available elsewhere, either from physically redundant sensors or from observers/Kalman estimators based on analytical redundancy (Wu, Thavamani, Zhang, & Blanke, 2006). However, once an actuator fails, the degree of the system control redundancy and the available actuator capabilities are reduced. If the original performance is still to be maintained, this will force the remaining actuators to work beyond their normal duties to compensate for the handicaps caused by failed actuators. This is highly undesirable in practice due to the physical limitations of the actuators. The consequence of a so-designed FTCS may lead to actuator saturation, or worse still, may cause further damage. Therefore, trade-offs between achievable performance and available actuator capability should be carefully examined in all FTCS designs. This situation is often referred to as graceful degradation in performance. Recent work in this area can be found in (Jiang & Zhang, 2006; Zhang & Jiang, 2001c, 2003) and the references therein. Design methods to achieve graceful performance degradation have been developed based on the concepts of single- and multiple-model based model-following and command input management techniques (Jiang & Zhang, 2006; Zhang & Jiang, 2003). Further investigation on this topic remains an important issue.

4.4. Stability and stability robustness

Stability is one of the primary requirements in any control system. In the context of FTCS, specifications for the system stability falls into three durations of system operations: (1) fault-free period; (2) transient period during the reconfiguration; and (3) steady-state period after the reconfiguration. Furthermore, as in any practical control system, robustness in stability and performance are also extremely important (Patton, 1993). For stability robustness, the feedback controllers must be designed such that the closed-loop system is stable in the presence of uncertainties. This is a well investigated area on its own in control engineering (Zhou, Doyle, & Glover, 1996). However, this issue has not been addressed extensively in AFTCS.

In the recent development on stability analysis for AFTCS, several notable works have been done. For example, theoretical research on the stochastic stability of AFTCS in the presence of noise, modelling uncertainties, fault detection time-delay, decision errors, and actuator saturation have been conducted (Mahmoud, Jiang, & Zhang, 2001, 2002; Mahmoud et al., 2003a; Mahmoud, Jiang, & Zhang, 2003b; Shi, Boukas, Nguang, & Guo, 2003), which are the extensions to (Mariton, 1989, 1990; Srichander & Walker, 1993) along the line for modelling the fault process, the FDD process and the control reconfiguration process as independent Markov processes. Stability analysis of gain scheduled FTCS has been addressed in (van der Sluis, Mulder, Bennani, & Schram, 2000; Wise & Sedwick, 1998) under the framework of linear matrix inequality (LMI). A combined analytical and simulation-based approach for the stability analysis of reconfigurable systems with actuator saturation has been introduced in (Bateman, Ward, Monaco, & Lin, 2002). Such simulation-based stability analysis first appeared in (Monaco et al., 1997). By using the LMI optimization technique for a multiple-model structure, a stability guaranteed FTCS against actuator failures has been developed (Maki, Jiang, & Hagino, 2004). In Boskovic and Mehra (2002), the stability of the overall reconfigurable control system in a multiple-model based reconfigurable flight control scheme has been demonstrated using multiple Lyapunov functions. However, stability analysis and stability robustness for real-time reconfigurable control systems in practical environment will still need further investigation.

4.5. AFTCS design for nonlinear systems

In practice, most of engineering systems are nonlinear. Hence it is necessary to consider AFTCS for nonlinear systems. A conventional approach to solving a nonlinear reconfigurable control problem is to design normal and reconfigurable controller based on linearized models around certain operating conditions (equilibrium points). The gain scheduling (Moerder et al., 1989), multiple model (Kanev & Verhaegan, 2000; Maybeck & Stevens, 1991; Theilliol, Sauter, & Ponsart, 2003), or sliding modes (Hess & Wells, 2003; Shtessel, Buffington, & Banda, 1999, 2002) approaches have been used. However, most of the work either considered fault scenarios or operating condition changes, but not both. Since the operating condition changes can be associated with the Mach number or dynamic pressure changes in the case of an aircraft, while the fault-induced change can be associated with identified fault parameters such as control effectiveness reduction, it is straightforward for the gain scheduling type approaches to take into account changes caused by both faults and operating condition variations. In general, however, how to design AFTCS which can work effectively in the entire range of general nonlinear systems and how to distinguish the changes induced by faults from that by operating conditions still remain to be investigated. In order to handle nonlinear systems beyond using linearized models, several reconfigurable control schemes, such as feedback linearization (Ochi & Kanai, 1991; Ochi, 1993), nonlinear dynamic inversion (Bacon, Ostroff, & Joshi, 2001; Doman & Ngo, 2002), backstepping (Zhang, Polycarpou, & Parisini, 2001), neural networks (Calise, Lee, & Sharma, 2001; Kabore & Wang, 2001; Napolitano, Neppach, Casdorph, & Naylor, 1995b; Napolitano, An, & Seanor, 2000; Wang & Wang, 1999; Wise et al., 1999), nonlinear regulator (Bajpai, Chang, & Kwatny, 2002), and Lyapunov methods (Polycarpou, 2001; Qu, Ihlefeld, Jin, & Saengdeejing, 2003) have been developed recently. However, effective design methods for dealing with nonlinear FTCS issues are not yet available. As will be discussed in the following section, FTCS design to deal with nonlinearity introduced by constraints of input and state/output variables is another challenging issue.

4.6. Dealing with input, state, and output constraints

Designing control systems with constraints on input and state/output variables is currently an active research topic, particularly in the area of control system design dealing with actuator amplitude and rate saturations (Hu & Lin, 2001; Kapila & Grigoriadis, 2002). Generally speaking, there are two types of approaches to deal with such issues: one relating to controller design (Mhaskar, Gani, & Christofides, 2006; Pachter, Chandler, & Mears, 1995) and the other using command (reference) management techniques, e.g. command (reference) governor (Zhang & Jiang, 2003), or command shaping and limiting (Bodson & Pohlchuck, 1998; Eberhardt & Ward, 1999).

Research on reconfigurable control system designs in the presence of actuator amplitude and rate saturation has been carried out in (Boskovic, Li, & Mehra, 2001; Jiang & Zhang, 2006; Mhaskar et al., 2006; Pachter et al., 1995; Shtessel et al., 2002; Zhang & Jiang, 2003). However, there are still many open problems in the framework of multi-input and multi-output (MIMO) systems.

4.7. Coping with FDD uncertainties and reconfiguration delays

Accurate and timely fault estimation/identification are important antecedents for satisfactory control reconfiguration. In practice, however, it is inevitable to have some estimation or identification errors (Bodson, 1993; Jiang & Zhao, 1998; Mahmoud et al., 2003b), which are referred to as *FDD uncertainties*. There are also time-delays and false alarms associated with FDD decisions (Mariton, 1989). Rapid and reliable detection and diagnosis of faults are necessary for the performance in AFTCS. In addition to enhancing the performance of FDD schemes, another way is to take into account these uncertainties in the reconfigurable controller design process and to reduce their effects as much as possible (Mariton, 1989; Mahmoud et al., 2003a, 2003b; Yang & Stoustrup, 2000).

Due to the abrupt changes in the system characteristics induced by faults, for any parameter estimation algorithm, it takes time for the estimated parameters to converge to true values. By using certain accelerating mechanisms, e.g., forgetting factor techniques (Wu et al., 2000b; Zhang & Jiang, 2002a), the post-fault system parameters could be obtained quickly. Other potential strategies to deal with such issues are, for example, bounding parameter estimation and the associated robust reconfigurable control design (Jiang & Zhao, 1998, 1999), multiple-step (progressive) reconfiguration (Staroswiecki, Yang, & Jiang, 2006; Zhang & Jiang, 1999; Zhang et al., 2001), and other approaches based on robust control (Campos-Delgado & Zhou, 2003; Wu & Chen, 1996; Wu, 1997; Yang & Stoustrup, 2000) and LMIs techniques (Chen, Patton, & Chen, 1999; Kanev & Verhaegen, 2003; Maki et al., 2004; Shin, 2005). New and practical approaches to deal with such FDD uncertainties and time-delays and desirable trade-offs between performance of FDD and control reconfiguration deserve further investigation.

4.8. On-line identification of closed-loop systems for reconfigurable control

Recent research activities on a self-designing controller (Monaco et al., 1997; Ward et al., 1998), RESTORE (Brinker & Wise, 2001; Buffington et al., 1999; Eberhardt & Ward, 1999), F-15 ACTIVE and IFCS (Anonymous, 2007b; Napolitano et al., 2001; Song et al., 2002), and the AMASF (Elgersma & Glavaski, 2001; Glavaski, Elgersma, & Lommel, 2003) have all focused on specific fault-tolerant control laws which rely on on-line estimates of aircraft parameters. In addition, as a continuation of the self-repairing flight control systems program, system identification schemes suitable for adaptive and reconfigurable control have been developed in (Chandler et al., 1995; Smith, Chandler, & Pachter, 1997). The need of system parameter identification in reconfigurable control has also been emphasized in (Jiang, 1994b; Morari & Lee, 1999; Maciejowski & Jones, 2003). On-line system identification and parameter estimation have played an important role in the reconfigurable controller design, and in turn, in the overall performance of AFTCS. Challenges in this area may include (1) how to deal with the collinearity in identification algorithms; (2) how to obtain accurate parameter estimates on-line and real-time in the presence of poor input excitation; (3) how to deal with adverse interactions between the identification and the control schemes in a closed-loop setting.

4.9. Management of redundancy and re-distribution of control efforts

In a conventional aircraft, there are three major control effectors: aileron, elevator and rudder, for three rotational axes. Aircraft flight control systems are designed utilizing one control effector for each rotational degree of freedom. Essentially, the aileron is used differentially to produce a rolling moment, the elevator can generate a pitching moment, and the rudder controls the yawing moment of the aircraft. The control allocation problem is defined as the determination of the positions/deflections of control effectors which generate a given set of desired moments specified by a pilot through the control stick inside the cockpit. In a traditional airplane, with three desired moments and three independent control effectors to generate these moments, a unique solution can be found. However, to increase the reliability, maneuverability and survivability of modern aircrafts, control effectors are no longer limited to these three. Many more control effectors have been introduced. As examples, there are 11 individual control effectors in an innovative control effectors tailless aircraft and 14 independent control surfaces in F-15 ACTIVE (Buffington et al., 1999; Eberhardt & Ward, 1999; Wise et al., 1999). With an increase in the number of redundant control effectors, the problem of allocating these controls to achieve the desired moments becomes non-unique. Such redundancy has called for effective control allocation or re-allocation (in case of actuator failures) to distribute the required control moment over available effectors. The objective of control (re)allocation is to choose a configuration of the control effectors (actuators) to meet a specified objective, subject to saturation constraints. In the case of actuator failures, it is desirable to "reconfigure" the control allocation scheme (re-allocation) in order to make best use of the remaining healthy actuators (Davidson, Lallman, & Bundick, 2001; Zhang, Suresh, Theilliol, & Jiang, 2007). Existing control allocation algorithms which have potential to be used for reconfigurable control allocation include pseudo-inverse, modified pseudo-inverse, direct allocation, constrained optimization methods based on linear programming or quadratic programming, fixed-point method or their combination (Bodson, 2002; Buffington et al., 1999; Burken, Lu, Wu, & Bahm, 2001; Davidson et al., 2001; Durham, 1993; Enns, 1998; Page & Steinberg, 2000). The existing methods can also be classified as direct and mixed/error/control optimization methods (Bodson, 2002). Even though the control allocation is primarily developed for flight control, it has also been applied to marine vehicles (Omerdic & Roberts, 2004; Podder, Antonelli, & Sarkar, 2001a; Podder, Antonelli, & Sarkar, 2001b; Sarkar, Podder, & Antonelli, 2002) and other applications. For new development, evaluation and challenging issues on the subject, readers are referred to (Bodson, 2002; Boskovic & Mehra, 2002; Burken et al., 2001; Davidson et al., 2001; Durham, 1993; Enns, 1998; Harkegard & Glad, 2005; Page & Steinberg, 2000) for details.

4.10. Transient/transition management techniques

In FTCS, undesirable transients may occur during the controller reconfiguration process. The transients may be harmful to the safe operation of the system. The consequences of these transients may cause saturations in actuators, and worse still, damage to components in the system. Therefore, such transients should be minimized as much as possible. However, how to manage or reduce these transients during a controller reconfiguration is still an open issue. Very few results are available in the literature, although several works have been done, see, for example, refer to (Guler, Clements, Wills, Heck, & Vachtsevanos, 2003; Kovacshazy, Peceli, & Simon, 2001; Simon, Kovacshazy, & Peceli, 2000; Simon et al., 2002; Zhang & Jiang, 1999; Zhang & Jiang, 2003). More comprehensive treatment on the transition management for reconfigurable control systems can be found in (Guler et al., 2003).

The potential solutions in reducing reconfiguration transients may lie in how to manage the system/controller states or command inputs. A systematic approach in solving such an issue is proposed (Guler et al., 2003; Simon et al., 2002).

4.11. Real-time issues and fault-tolerant networked control systems

Due to the dynamic nature of a control system and real-time environment of FDD and controller reconfiguration, AFTCS must be able to detect, identify and accommodate faults as quickly as possible. In other words, all the subsystems in AFTCS should be operating in an on-line and real-time manner. In this regard, AFTCS are real-time systems. There should be a hard deadline in taking actions for controller reconfiguration to avoid putting the overall system in a potentially risky situation. To achieve successful control system reconfiguration, the FDD scheme should be able to provide accurate and the most up-to-date information (including post-fault system models) about the system in real-time. The reconfiguration mechanism should be able to synthesize the reconfigured controller as soon as possible to maintain the desired stability margins with acceptable performance within the time constraints and also those of control inputs and states/outputs. The trade-offs among various design objectives also need to be carried out on-line in real-time. Such a real-time issue has not been dealt with to a satisfactory level, although it is a critical issue for any real-time system (Bennett, 1994; Hammett, 1999; Kopetz et al., 1991; Kopetz, 1997).

Tightly related to the above real-time issue, consideration of communication networks in the FTCS, or fault-tolerant networked control systems have recently attracted attention significantly (Anonymous, 2007c; El-Farra, Gani, & Christofides, 2005; Huo & Fang, 2007; Kambhampati, Patton, & Uppal, 2006; Sauter, Boukhobza, & Hamelin, 2006; Wang, Huang, & Tan, 2004). Fault-tolerant designs in such networked control systems are especially challenging due to timing issues in the networked environment. Heterogeneous software and hardware components, and multiple operating modes must run in harmony in a single system. Due to the dynamic real-time behavior in such systems, fault-tolerant mechanisms should be provided to enable them to adapt to the new operating conditions through continuous self-repairing. This is obtained through automatic calculation of appropriate remedial actions for a new set of control parameters in order to avoid certain damaging effects of a fault. In such FTCS, in addition to commonly considered system component failures, sampling jitters and control delay caused by real-time constraints, network-induced delay and packet losses are the main challenges to be tackled (Anonymous, 2007d; El-Farra et al., 2005; Huo & Fang, 2007; Kambhampati et al., 2006; Sauter et al., 2006; Wang et al., 2004). For the new development of a European project "Networked Control Systems Tolerant to Faults (NeCST)", interested readers are referred to the project website and the associated workshops (Anonymous, 2007d).

4.12. Safety, reliability and reconfigurability analysis and assessment

As it is well-known, the primary objective for introducing redundancy and fault tolerance in a system is to increase safety and reliability. Safety is the ability of a system to prevent any danger to human life, equipment or environment, while reliability is the ability of a system to perform required functions correctly over a given period of time under a given set of conditions. Control reconfigurability assesses the ability of system to allow performance restoration in the presence of faults (Wu, Zhou, & Salmon, 2000c).

In designing FTCS, one may ask the following questions: Do such techniques really increase the safety and the reliability of the overall system? How to measure such improvement quantitatively? Efforts have been made to provide quantitative measures for reliability and reconfigurability/recoverability of FTCS, see for example (Blanke et al., 2001; Frei, Kraus, & Blanke, 1999; Staroswiecki, 2002; Staroswiecki & Gehin, 2001; Wu, 2004; Wu & Patton, 2003; Wu et al., 2000c). As pointed out in (Wu, 2004), reliability has not been treated as an objective criterion which guides FTCS design in an integrated manner. One of the difficulties lies in establishing functional linkages between the overall system reliability and the performance improvement contributed to controls and diagnosis functions. Automated and real-time analysis for the reliability and reconfigurabil-ity of AFTCS and effective reconfiguration strategies based on reliability analysis are some worthwhile topics for further development (Guenab, Theilliol, Weber, Zhang, & Sauter, 2006).

4.13. Practical considerations in applications of FTCS

Even though a significant effort has been made recently in the field of FTCS, many algorithms and methods have been developed in different application areas, novel practically-applicable control structures and design methods which can better fit into practical applications still remain an important task in the field of FTCS (Blanke et al., 1997, 2001, 2003, 2006; Patton, 1997b; Staroswiecki & Gehin, 2001; Zhou & Ren, 2001). From a theoretical point of view, unified, systematic theory and design techniques need to be developed. From a practical point of view, efforts in redundancy management, real-time fault propagation and reconfig-urability analysis, reconfigurable controller design with consideration of some practical issues, integration of FDD and reconfigurable control, as well as practical implementation in conjunction with redundant hardware and software structure and fault-tolerant communication networks are among the important topics for future research.

With rapid advance in microelectronics and mechatronics technologies, intelligent actuators and sensors possessing self-diagnostic properties are available (Isermann & Raab, 1993; Clarke, 1995, 2000; Edgar et al., 2000; Isermann et al., 2002; Tombs, 2002; Tortora, 2002; Tortora, Kouvaritakis, & Clarke, 2003; Benitez-Perez & Garcia-Nocetti, 2003). These intelligent instrumentations will have significant impact on the overall structure and implementation of AFTCS. Those built-in diagnostic capabilities should be fully exploited in AFTCS design.

On the other hand, the rapid development of control systems, from a single control loop implemented on a single microprocessor to distributed control systems with integration of control loops, sensors, actuators on a platform with networked computing, communication and control systems, reveals the deficiency and limitations of existing FTCS. So far most of the development in AFTCS focused mainly on algorithmic rather than on overall system level architecture and technical platform used. New technologies for integrated designs of the entire AFTCS together with associated implementation platforms (hardware, software, computing platforms, and communication protocols) are highly desirable (Blanke et al., 1997; Campelo et al., 1999; Carcia, Ray, & Edwards, 1995; Hammett, 1999; Kopetz & Bauer, 2003; Lygeros, Godbole, & Broucke, 2000; Murray, Astrom, Boyd, Brockett, & Stein, 2003; Wills et al., 2001).

Overall, fault-tolerant control is a complex interdisciplinary research field that covers a diverse range of engineering disciplines, such as modelling and identification, applied mathematics, applied statistics, stochastic system theory, reliability and risk analysis, computing, communication, control, signal processing, sensors and actuators, as well as hardware and software implementation techniques. To develop practical AFTCS, FDD schemes and reconfigurable controllers should be designed in conjunction with techniques in fault-tolerant/reconfigurable computing, fault-tolerant communication networks (El-Farra et al., 2005; Wang et al., 2004), fault-tolerant software (Guler et al., 2003; Provan & Chen, 2001; Pullum, 2001); fault-tolerant real-time/embedded systems (Avresky, Lombardi, Grosspietsch, & Johnson, 2001; Ahlstrom & Torin, 2002; Campelo, Yuste, Gil, & Serrano, 2001); advances in intelligent sensors and actuators (Clarke, 2000; Isermann & Raab, 1993; Isermann et al., 2002; Tombs, 2002; Tortora, 2002); advances in microelectronics/mechatronics (Isermann, 1996; Isermann, 2000; Kortüm, Goodall, & Hedrick, 1998; Ollero et al., 2006) and advanced electronic devices such as FPGA (Field Programmable Gate Array); and hardware/software co-design and implementation. In this regard, not only the reconfigurable controller and the associated FDD design techniques themselves, but also techniques relating to real-time computing and communication, and reconfigurable hardware/software implementation have to be considered as a whole to achieve a functional AFTCS.

5. Conclusions

As an emerging and active area of research in automatic control, fault-tolerant control has recently attracted more and more attention. A brief technical review and bibliography listing on the historical and new development in active fault-tolerant control systems (AFTCS) have been presented in this paper. The existing approaches in fault detection and diagnosis (FDD) and reconfigurable control (RC) are outlined. Some open problems and current research activities have been discussed and more than 300 references have been categorized. Since FTCS involve many disciplines, there are many related publications in each individual topic in AFTCS, and due to space limitation, the review reported in this paper is in no way exhaustive. For the sake of easy access to the listed references and with the interest of space, emphasis has mainly been placed on refereed journal papers. Many conference publications could not be included in spite of our best effort. We apologize in advance for any omission.

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