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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 fault-tolerant control systems (FTCS) is presented. The existing approaches for fault detection and diagnosis (FDD) and reconfigurable control are considered with emphasis on the reconfigurable/restructurable controller design techniques. Several open problems and current research topics are addressed. 250 references in the open literature are listed to provide an outline of the historical and recent development in the field. The review reported in this paper is in no way to be complete, we apologize in advance if any of the existing works were left out. We encourage readers to communicate with us for any additional information.

Keywords: Fault-Tolerant Control Systems (FTCS), Active Fault-Tolerant Control Systems (AFTCS), Fault Detection and Diagnosis (FDD), Reconfigurable Control (RC), Bibliographical Review.

1. INTRODUCTION

Over the last three decades, the growing demand for reliability, maintainability, and survivability in dynamic systems has drawn significant research in fault detection and diagnosis (FDD). Such efforts have led to the development of many FDD techniques, see, for example the survey papers [1–21] and books [22–37]. On a parallel path, research on reconfigurable/fault-tolerant control systems (FTCS) has increased progressively since the initial research on restructurable control and self-repairing flight control systems begun in early 1980s [38,39]. An early excellent work on the design issues for fault-tolerant aircraft control was given in 1985 [40]. Other early (tutorial) papers on the subject of FTCS include [41,42,38,43]. More recently, fault-tolerant control has attracted more and more attention in both industry and academic communities due to rapidly increasing demands for higher system performance, productivity and cost efficiency. Several review/survey papers on FTCS have appeared since 1990s [44–54,21]. However, compared to FDD, very few books on the subject of FTCS have been published until a recent publication [55], although there are several book chapters are available [56–60]. As a milestone, the first IFAC Symposium on Fault Detection, Supervision and Safety for Technical Process (SAFEPROCESS) was held in 1991, which was followed by an IEE Colloquium on Fault Diagnosis and Control System Reconfiguration held in 1993. More recently, invited tutorial sessions, workshops and plenary talks on the topic have frequently appeared in many conferences such as ACC, CDC, ECC, AIAA GNC Conference, IFAC World Congress and IFAC SAFEPROCESS, just to name a few. A special issue on reconfigurable flight control has appeared in [61].

Even though the extensively individual research on FTCS has been carried out, the systematic concepts, design methods, and even its terminology are still not standardized. Recently, effort has been made to unify terminology definitions [17,52–55]. In addition, due to historical reasons, most of the research on FDD and reconfigurable/restructurable control were carried out independently. More specifically, most of the FDD techniques are developed as a diagnostic or monitoring tool, rather than an integral part in FTCS. Clearly, some existing FDD methods may not satisfy the need of controller reconfiguration. On the other hand, most of the reconfigurable controls are carried out with the assumption of perfect information from FDD. Very little attention has been paid to the following problems, e.g., from the reconfigurable control (RC) design viewpoint what is the need and requirement from the FDD; what can be provided by the existing FDD techniques for FTCS design; how to systematically analyze the interaction between FDD and RC and to design the FDD and RC in an integrated manner for on-line and real-time applications? Many challenging issues still remain for further research and development. One of the motivations of this paper is to provide a brief review on the development in FTCS and to recognize some open and challenging problems for our future research. It is our hope that this effort can also provide some useful information to researchers and engineers in the field and play certain role to facilitate the research and development of FTCS.

As it is well-known, FTCS are control systems that possess the ability to accommodate system component failures *automatically*. They are capable of maintaining overall system stability and acceptable performance in the event of such failures. Generally speaking, FTCS can be classified into two types: *passive* (PFTCS) and *active* (AFTCS). In PFTCS, controllers are designed to be robust against a class of presumed faults [40]. The basic idea is to make the closed-loop system robust against uncertainties and some restrictive faults. Therefore, this approach needs neither FDD schemes nor controller reconfiguration but with limited fault-tolerant capability. Discussions on PFTCS are beyond the scope of this paper and interested readers are referred to [62–68] and the references therein for recent development.

In contrast to the 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 [44,49,53]. FTCS were also known as self-repairing[39], reconfigurable[69], restructurable [38,70], or self-designing [71] control systems. In such control systems, the controller compensates for the effects of faults either by selecting a pre-computed control law (projection-based methods) [69,72,47,73] or by synthesizing a new control scheme on-line (online automatic control redesign methods) [70,49,74]. To achieve a successful control system reconfiguration, both methods relies on a real-time FDD scheme to provide the most up-to-date information about the system. Typically, AFTCS consist of three or four parts: 1) a reconfigurable controller, 2) a FDD scheme, 3) a controller reconfiguration mechanism, and 4) a command/reference governor. Key issues are how to design: a) a controller which is reconfigurable or restructurable, 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 can organize the reconfigured controller in such a way that the pre-fault system performance can be recovered as much as possible in the presence of uncertainties and time-delays in FDD and under the constraints of control input and state limits, in particular constraints on actuator amplitude and rate limits. The critical issue in any AFTCS is the limited amount of time available for the FDD and for the control system reconfiguration. Besides, efficient utilization and management of redundancy (in hardware, software and communication databus), stability, transient and steady-state performance, robustness to noises, uncertainties and disturbances, and interaction among the above outlined subsystems are some of extremely important issues in the design of AFTCS. In view of the above issues, a bibliographical review on possible solutions to the above design issues in AFTCS is provided in this paper with emphasis on reconfigurable control design techniques. Several open problems and current research topics are addressed with the associated literature.

The paper is organized as follows: In Section 2, the design objectives and structure of AFTCS are discussed. Review and classification of existing reconfigurable control algorithms are provided in Section 3. A brief review on FDD is given in Section 4. Several recognized challenges and open problems in designing AFTCS are discussed in Section 5 followed by conclusions given in Section 6.

2. OBJECTIVES AND STRUCTURE OF AFTCS

The design objectives for FTCS should include the dynamic and the steady-state performance not only under the normal operation, but also under faults. It is important to point out that the emphasis on system behaviors in these two modes of operation can be significantly different. During the normal operation, one may want to place more emphasis on the quality of the system behavior. In the presence of a fault, however, how the system survives with an acceptable degraded performance become a predominant issue.

The overall structure of a typical AFTCS is shown in Fig. 1. It consists of four major components: a) an on-line and real-time FDD scheme; b) a reconfiguration mechanism; c) a reconfigurable controller; and d) a command/reference governor. In the FDD module, both the fault parameters and the system state variables need to be estimated on-line in real-time. Online FDD schemes for different type of faults need to be presented to make reliable and timely decision for activation of the control reconfiguration mechanism. Based on the on-line information on the post-fault system provided by the FDD module, the reconfigurable controller should be designed automatically to maintain the stability and specified dynamic and steady-state performance of the system. In addition, to ensure the closed-loop system be able to track a command input or a reference model/trajectory even in the event of faults, a reconfigurable feedforward controller needs to be synthesized to achieve command tracking. In the case of performance degradation and actuator saturation avoidance being required, a command/reference governor may need to be used to adjust command input or reference trajectory automatically or provide advisory information to human operators in the event of faults.

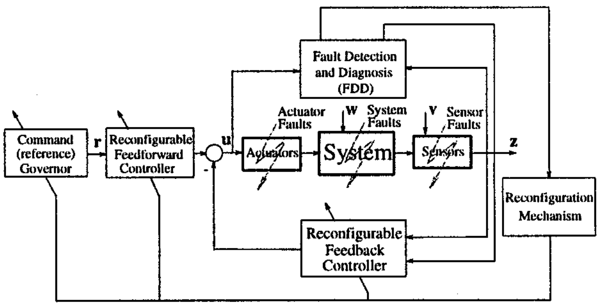

Fig. 1. General structure of FTCS.

The design objective of AFTCS is then to 1) design a FDD scheme providing as precise as possible information about a fault (time, type and magnitude) and the post-fault model, and 2) design a new controller (reconfigurable/restructurable) in response to and compensating for the fault-induced changes in the system, such that the stability and acceptable closed-loop system performance can be maintained.

In the design of such AFTCS, if not only the parameters in the feedback and feedforward controllers need to be recalculated in the event of faults, but also the structure of the new controllers (in terms of the or-der of the controllers, the numbers and the types of the controllers) needs to be changed accordingly. The corresponding FTCS are often referred to as restructurable control systems [44,49,75], in differentiating from the reconfigurable control systems which involve only control parameters recalculation.

3. CLASSIFICATION OF EXISTING RECONFIGURABLE CONTROL APPROACHES

3.1 *Classification According to Control Algorithms*

In general, the existing model-based reconfigurable control design methods fall into one of the following approaches: linear quadratic regulator; eigenstructure assignment; pseudo-inverse; model-following; adaptive control; multiple-model; gain scheduling or linear parameter varying; variable structure and sliding mode control; model predictive control; feedback linearization and dynamic inversion, etc. Detailed classification of existing fault-tolerant control (FTC) approaches can be carried out based on the criteria such as 1) mathematical tools used; 2) design approach used; and 3) the way achieving reconfiguration. Such a classification is given as following:

- Mathematical tools used
  - Linear Quadratic Regulator (LQR)
  - Eigenstructure Assignment (EA)
  - Adaptive Control (AC)
  - Multiple Model (MM)
  - Gain Scheduling (GS)
  - Linear Parameter Varying (LPV)
  - Pseudo-Inverse (PI) or Control Mixer
  - Model Following (MF)
  - Variable Structure(VS)/Sliding Modes(SM)
  - Feedback Linearization (FL)
  - Dynamic Inversion (DI)
  - Model Predictive Control (MPC)
  - H_∞ and other Robust Control techniques
  - Quantitative Feedback Theory (QFT)
  - Linear Matrix Inquality (LMI)
  - Neural Networks (NN)
  - Fuzzy Logic (FL)
  - Combined methods
- Design approach used
  - Pre-computed control laws
    - MM
    - GS/LPV
    - QFT
    - LMI
  - On-line automatic redesign
    - LQR
    - EA
    - PI
    - FL/DI
    - MF
    - VS/SM
    - MPC
- The way achieving reconfiguration
  - Following
    - State–MF
    - System matrix–PI
    - Eigenstructure–EA
  - Switching
    - MM
    - GS/LPV
    - VS/SM

A partial list of existing approaches in fault-tolerant control systems is presented in Table 1.

3.2 *Classification According to Application Areas*

Fault-tolerant systems and associated control designs have inherently wide and diverse engineering applications, which range from a) safety-critical systems (such as aircraft, helicopters, spacecraft and automobiles, nuclear power and hazardous chemical plants); b) life-critical systems (such as tele-robots for surgery, implanted heart monitors, nanoscale diagnostic instruments, digital prostheses and other medical devices, as well as ground traffic control and automated highway systems); c) mission-critical systems (such as avionics and air traffic control systems, defense systems, spacecraft and space stations, autonomous aerial/space/underwater vehicles, robots used in industrial processes, and communication networks); and d) cost-critical systems (such as large-scale space structures, drive-by-wire automobiles, distributed process control, computing and communication networks).

Table 1. A partial list of existing approaches in FTCS.

Design approaches	References
Linear quadratic regulator	[70,69,76]
Pseudo-inverse	[77–81]
Model following	[76,82,78,83–85,74]
Eigenstructure assignment	[86,64,87,73,74]
Adaptive control	[88,72,89,90]
Multiple-model	[72,91,47,92,93,73,94]
Gain scheduling/LPV	[69,47,95–98]
VS and sliding mode control	[99–102]
Model predictive control	[103,71,104–106]
Nonlinear control	[107–109,79,110]
QFT	[111–114]
H_∞	[62,115–117]
LMI	[118–120,97,68]
Neural network and fuzzy logic	[46,121–132]
Expert systems	[133,134]
Integrated FDD and control	[135–138,126,139,81,140,73,74]
Overall architecture and others	[50,141,142]

The initial motivation for the research on reconfigurable FTCS was in the area of avionics and flight control systems for the purpose to improve the reliability and safety of aircraft, which was activated directly or indirectly because of the two aircraft accidents in the Delta Flight 1080 on April 12, 1977 and an American Airlines DC-10 crash at Chicago on May 25, 1979 [38]. Therefore, as it will be seen from Table 2, a large amount of research has been carried out for flight control systems. Several reconfigurable flight control systems have been flight tested [143,71,144,145]. However, there seems still no certified technique having been used to commercial or military service yet. Besides, interests in fault diagnosis and fault-tolerant control of nuclear power plants have been intensified after the Three Mile Island incident and the tragedy at the Chornobyl nuclear power plant on April 26, 1986 [146–148].

With the rapid advances in microelectronics, mechatronics, intelligent actuator and sensor techniques, and computing technologies, and motivated by rapidly increasing demands for higher system performance, product quality, productivity and cost efficiency beyond the conventional safety-critical aerospace and nuclear power systems, FTCS design is rapidly becoming a key issue in commercial product development and system design such as drive-by-wire automobiles [21], manufacturing [149] and other industrial systems. There is a trend that concepts and methodologies developed in the fly-by-wire fault tolerant flight control systems (also other systems such as aerospace, nuclear, railway, ships) have been extended to more general engineering systems such as automotive and automated highway systems, (petro) chemical plants, power systems, robots, and medical systems. A partial list of publications in some application-oriented research is given in Table 2.

Table 2. Application-oriented research in FTCS.

Applications	References
Aircraft/helicopters	[70,77,69,76,71,157,153,158] [159,129,144,160,73,74]
Spacecraft and structures	[161,138,50]
Automotive and highway systems	[162,163,102,21,164,165]
Autonomous vehicles	[166,47,139,167–170,141,171]
Engine and propulsion control	[172–174,130,175]
(Nuclear) power systems	[176,177,146–148,178]
Chemical/petrochemical plants	[179–181]
Robots	[182–185]
Other engineering systems	[136,186,187,128,188–197]

4. CLASSIFICATION OF EXISTING FDD APPROACHES

As mentioned previously, many FDD schemes have been developed in the last three decades. However, there are few results on the systematic research about the role of FDD in AFTCS and which FDD methods are more suitable to the context of AFTCS [49]. A preliminary research in [49,150] 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. However, the information from the state estimation based algorithms may not be detailed enough for subsequent control system reconfiguration. Parameter estimation based schemes are more suitable in this respect. Hence, the combination of state and parameter estimation schemes is to be more appropriate [151,74]. In fact, there is a tendency to use parameter identification techniques for reconfigurable flight control systems [152–156]. The detailed discussion and classification of FDD approaches is omitted here due to limitation of space.

5. OPEN PROBLEMS AND CURRENT RESEARCH TOPICS IN ACTIVE FTCS

Since the nature and severity of faults are generally unknown *a priori*, and the post-fault system dynamics are also unknown, FDD techniques have to be used to construct the post-fault system model for AFTCS design. The performance of the AFTCS will depend on many factors, such as the speed and the accuracy of the FDD scheme, the availability of the remaining healthy actuators, the strategy to utilize the redundancy, the type of control strategies adopted in the reconfigurable controller design, and the manner integrating/interacting each components in the overall AFTCS. Due to the real-time and dynamic nature of the system, there is only a very limited amount of time available to carry out the post-fault model construction and reconfiguration actions. The trade-off among various design objectives and interaction among different subsystems have to be carried out on-line in real-time. All these raise challenging issues to the design of AFTCS, although significant development in FTCS has been achieved recently. Such issues are identified and discussed in the following sections.

5.1 *Redundancy and Redundancy Management*

Redundancy is the key ingredient in any fault-tolerant systems. For example, almost all of modern military aircraft and the new generation of civil aircraft such as Boeing 777 and Airbus A320/330/340 have used triplex- or quadruplex-redundant actuation systems, flight control computer and databus systems, air data and motion sensor systems [198,199]. Such redundancies are currently implemented mainly by hardware or software.

Since late 1970s, with the development and its use in service of the fly-by-wire (FBW) flight control systems, flight control computer become a necessary and critical component in the automated flight control systems. This motivated the development of the concept of "analytical redundancy" which is based on signals generated from a mathematical model of the system for fault detection, diagnosis and accommodation. It is this analytical redundancy having lead to significant research and development of FTCS. In fact, reconfigurable/fault-tolerant control introduces a new view of utilizing redundancy, where reliability is achieved through software rather than hardware only. However, through the use of analytical redundancy, it is possible to reduce the level of hardware redundancy but not to replace hardware redundancy [21]. Caution may need to be paid for how to efficiently utilizing and embedding the analytical redundancy into the existing system's hardware redundancy [200,201]. This introduces challenging issues for AFTCS design regarding the overall fault-tolerant and redundant system architecture, optimal configuration of hardware and software redundancy in terms of trade-off between reliability and cost, as well as how to design and implement a fault-tolerant controller to maximally utilize and manage both physical and analytical redundancies to achieve design objectives. Besides, quantitative measure of the degree of redundancy is also important issue for research [64,65,202].

5.2 *Integrated Design of FDD and RC*

To build a truly functional AFTCS, it is important to examine all subsystems closely to make sure they can work in harmony. To be more precisely, from reconfigurable control (RC) viewpoint, one needs to examine what kind of information is needed from FDD to achieve a reasonable control strategy, and from the FDD point of view, one needs to know what types of information are deliverable. The demand and supply between these two subsystems should match, otherwise, the overall system will not work properly. An incorrect or much delayed FDD result may not only result in a loss of system performance, but also instability of overall system. An inappropriate RC mechanism based on incorrect FDD information will also lead to poor performance and even the loss of stability of the overall system. It is also very important to emphasize that the above actions are carried out within a limited time interval and in real-time manner. Investigation on the applicability, suitability and interaction of existing FDD approaches to the RC problem is still one of the open problems.

Efforts have been dedicated to combining different blocks of AFTCS together using integrated design approaches and study performance of the overall FTCS [136,203,148,126,139,204,159,188,81,102,140,73,74]. Along a different direction, an integrated approach to control and diagnosis is developed in [135], in which the control and diagnostic modules are designed together. New development along this line can be found in [137,206]. The issue of merging blocks of FTCS seems to be easy task in principle, unfortunately, this is not the case in reality. The main difficulty that arises when integrating the blocks of FTCS is that each individual block is assumed to operate perfectly and is readily available to provide decisions/actions instantaneously to other blocks. How to mitigate the adverse interaction between each blocks is an important issue to be further investigated [204]. How to balance the performance robustness during the system normal operation versus fault sensitivity at the time of a system component failure is also an important issue to be considered [115,116].

5.3 *Design for Graceful Performance Degradation*

In any FTCS design, one of the important issues to consider is whether to recover the original system performance completely or to accept some degree of performance degradation after occurrence of a fault. 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 [49,53]. In practice, in the case of sensor faults, the original system performance might be recovered as long as correct system output signals are available either from physically redundant sensors or from observers/Kalman estimators based on analytical redundancy. However, once an actuator fault occurred, the degree of the system control redundancy and the available actuator capabilities could be significantly reduced. If the design objective is still to maintain the original system performance, this may force the remaining actuators to work beyond the normal duty to compensate for the handicaps caused by the fault. This is highly undesirable in practice due to physical limitations of the actuators. The consequence of the so-designed FTCS may lead to actuator saturation, or worse still, to cause further damage. Therefore, trade-off between achievable performance and available actuator capability should be carefully considered in all FTCS designs. This situation is often referred to as graceful degradation in performance. Recent work along this line can be found in [184,85,207,208]. The design methods to achieve graceful performance degradation have been developed based on the concepts of model-following and command management [207]. However, systematic and optimal design strategies to avoid actuator saturation during the transient period of reconfiguration are still waiting for further investigation.

5.4 *Stability Analysis, Guarantee, and Robustness*

Stability is the primary requirement for any control systems. In the context of FTCS, requirement on system stability includes three periods of system operations: 1) fault-free period; 2) transient period during reconfiguration; and 3) steady-state after reconfiguration. Furthermore, as for any practical control systems, robustness in stability and performance is also extremely important for the control systems to be practically useful [45]. For stability robustness, the feedback controllers must be chosen such that the closed-loop system is stable in the presence of uncertainties. This is a large research area by itself in control field. However, this issue has not been addressed extensively in AFTCS.

For the recent development on stability analysis and the stability guaranteed FTCS design, 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 and errors, and actuator saturation have been conducted recently [209,210,224,55], which are extensions of [211–213] along the line for modeling the fault process, the FDD process and the control reconfiguration process as independent Markov chain processes. Stability analysis of gain scheduled FTCS were addressed in [118,120] under the framework of linear matrix inequality (LMI). A combined analytic and simulation-based approach for the stability analysis of reconfigurable systems with actuator saturation has been introduced in [214]. Such a concept of simulation-based stability analysis was first appeared in [71]. By using LMI optimization technique for a multiple-model structure, a stability guaranteed FTCS against actuator failures has been developed [215]. In [94], the stability of the overall reconfigurable control system in a multiple-model reconfigurable flight control scheme is demonstrated using multiple Lyapunov functions under the condition of the separation between identification and control arising in the context of indirect adaptive control. However, stability analysis and stability robustness for real-time reconfigurable control and in a more practical problem setting are still open problems.

5.5 *FTCS Design for Nonlinear Systems*

In practical engineering systems, most of systems are nonlinear. Hence there is a strong need to design FTCS being able to deal with such nonlinearity. Conventional approach to solving nonlinear reconfigurable control problem is to design normal and reconfigurable controller based on linearized model for certain operating condition/equilibrium point. Then the gain scheduling [69], multiple model [72,216], or sliding modes [99,100] approach can be used. However, most of work considered either fault scenarios or operating condition changes, not for both. Even though it is possible to use these approaches, for example, gain scheduling, to take into account of changes caused by both faults and operating condition variations in aircraft since the operating condition changes can be associated with the Mach number or dynamic pressure changes while the fault-induced change can be associated with identified fault parameters such as control effectiveness reduction. However, in general, how to design FTCS which can work effectively in the entire operating regimes of highly nonlinear systems and how to distinguish the changes due to failures or operating conditions are still challenging issues. Several reconfigurable control schemes such as feedback linearization [107,108], nonlinear dynamic inversion [79,110], backstepping [205], neural networks [122,129,127,159,217,193], quantitative feedback theory (QFT) [111,112], nonlinear regulator [218] approaches have been developed recently. However, effective design methods for truly solving nonlinear FTCS issue are still expecting. As will be discussed in the following section, FTCS design to deal with nonlinearity introduced by constraints of inputs and state variables is another challenging issue.

5.6 *Dealing with Constraints in Inputs and States*

Designing control systems with constraints of inputs and state variables is currently an active research topic, particularly, in the area of control system design dealing with actuator amplitude and rate saturation. There are extensive research in recent years, see several recently published books and the reference therein [219,220]. Generally, there are two type of approaches to deal with such saturation issues: 1) one relating to controller design part; and 2) the other using command (reference) management techniques, with different names in the literature such as command (reference) governor [207], or command shaping and limiting [221,204].

Research on reconfigurable control designs in the presence of actuator amplitude and rate saturation has been carried out in [103,222,207,208,100]. However, there are still many challenges in dealing with such saturation for MIMO systems in a more efficient way so that the developed strategies are more suitable to on-line and real-time applications.

5.7 *Dealing with FDD Uncertainties and Reconfiguration Delay*

Precise fault estimation/identification is an important antecedent of control reconfiguration. However, in practice, there usually exist some possible estimation or identification errors [223,117], which are referred to as *FDD uncertainties*. There are also time-delays associated with FDD and control reconfiguration. One of the design objectives for FTCS is to take into account of these FDD uncertainties in the design of reconfigurable controller and to reduce the effects of the time-delays as much as possible [211,224]. Such designed reconfigurable control can be referred to as robust reconfigurable control.

Due to the abrupt changes of the system caused by faults, for any parameter estimation technique, it requires some time before the estimated parameters converge to the real ones. By using certain speeding up mechanisms for parameter estimation, e.g., forgetting factor techniques [151,74], it can significantly help to obtain the post-fault system parameter quickly. Other possible strategies to deal with such problems are, for example, bounding parameter estimation and the associated reconfigurable control design [225], limited-time multiple (multi-step) reconfiguration [226,205], and more rigorous approaches exploiting robust control [115–117] and LMIs techniques [119]. New approaches to deal with such FDD uncertainties and time-delays and a good trade-off between performance in FDD and reconfiguration are issues for further investigation.

5.8 *Real-time Issues*

Due to the dynamic nature of the system and its real-time nature in executing the tasks of FDD and RC, AFTCS must be able to detect, identify and accommodate faults quickly. That is, all the subsystems in the overall AFTCS should be running in an on-line and real-time manner. There is a hard deadline in taking action for controller reconfiguration to avoid potential system destruction. In this sense, AFTCS can be viewed as real-time systems. To achieve a successful control system reconfiguration, the FDD scheme should be able to provide precise and the most up-to-date information (including post-fault system model) about the system as soon as possible after the fault occurrence. The reconfiguration mechanism should be able to synthesize the reconfigured controller as soon as possible to maintain system's stability with probably degraded performance under the timing constraints and also the constraints of control input and state limits. The trade-off among various design objectives have also to be carried out on-line in real-time. Such a real-time nature of the AFTCS has not been paid much attention yet, although it is a critical issue in real-time systems [227–229,201].

5.9 *On-line Identification for Closed-loop Systems with Reconfigurable Control*

Recent research programs, such as the self-designing controller [71], the RESTORE [144,154,204] and the F-15 ACTIVE [155,156], have developed specific fault tolerant control laws which used on-line estimates of aircraft parameters obtained from an on-line parameter identification scheme. Besides, as a continuation of the self-repairing flight control systems program, a system identification scheme for adaptive and reconfigurable control was developed in [152]. Therefore, on-line system identification and parameter estimation has played a very important role to the reconfigurable controller design, and in turn, the overall performance of FTCS. Challenges for such a closed-loop identification and control issue include 1) how to deal with the collinearity in the identification algorithms; 2) how to obtain accurate parameter estimates in online and real-time under the conditions of lacking sufficient input excitation and the need for more parameters to be estimated; 3) how to handle the adverse interaction between identification and control within the closed-loop.

5.10 *Control Re-allocation and Re-distribution*

In conventional aircraft, there are essentially three control effectors (such as aileron, elevator and rudder) to control the three rotational axes. However, to increase the reliability, maneuverability and operability of modern aircraft, many more control effectors have been introduced. As an example, there are 11 individual control effectors in an innovative control effectors tailless aircraft [159,204,154]. Such a control redundancy has created the need for a control allocation/re-allocation to distribute/redistribute the required control moment over the effector suite. Some existing control allocation algorithms are ganging, direct allocation, pseudo-inverse, modified pseudo inverse, linear programming, quadratic programming, fixed-point method or their combination [230,154,231–233]. The existing methods can also be classified as direct and mixed/error/control optimization methods [230]. For the new development, evaluation and challenging issues on the control allocation algorithms, readers are referred to [230–235,94] for details.

5.11 *Transient/Transition Management Techniques*

In FTCS, undesirable transients may occur when either the controller or the plant is reconfigured during the operation in response to fault-induced system changes or operating condition variations. The transients may be harmful to the systems and human bodies. The consequences of these transients may induce the saturation of amplitude and/or rate limits in actuators, and worse still, damage the components in the system. Therefore, these transients should be limited, or possibly reduced. However, how to manage or reduce these transients during controller reconfiguration is still a challenging issue. Very few results are available in the literature, although several works have been done in an attempt to provide a solution to the problem, see, for example [226,207,236–238]. More comprehensive treatment on transition management for reconfigurable control systems can be found in [238].

The challenges in reducing the reconfiguration transients lie in how to manage either system/controller states or command inputs for MIMO systems. Systematic way for solving such an issue is under way [238]. Some existing techniques in control systems and signal processing may provide useful information for the solution to reduce the reconfiguration transients, but extensions to MIMO case are still challenging issues.

5.12 *Safety, Reliability and Reconfigurability Analysis and Assessment*

As it is well-known, the primary objective for introducing redundancy and FTC is to increase the reliability and safety of a controlled system. Safety is the ability of a system not to cause a danger for human life, equipment or environment, while reliability is the ability of a system, or component, performs a required function correctly over a given period of time under a given set of fault conditions. Control reconfigurability assesses the system ability to allow performance restoration in the presence of faults [239].

By exploiting analytical redundancy and applying fault diagnosis and fault-tolerant control techniques, the primary objective is to introduce an alternative way for increasing system's safety and reliability. However, one may ask simple questions: if such techniques really increase the safety or reliability of the overall system? How to measure these criteria quantitatively? Efforts have been made to provide such quantitative measures for reliability and reconfigurability/recoverability of FTCS, see for example, [240,239] [53,54,241]. As pointed out in [241], reliability is rarely regarded as an objective criterion that guides FTCS design in an integrated manner. One of the difficulties lies in establishing a functional linkage between the overall system reliability and the performance defined for the controls and diagnosis. Automated and real-time analysis for the reliability and reconfigurability of FTCS is still waiting for further development.

5.13 *Other Open Problems and Applications of FTCS*

Even thought the significant development has been conducted recently in the field of FTCS, many algorithms and methods have been developed with different application areas as reviewed previously. However, new/novel practically-applicable control structures and design methods which can fit better into the practical engineering applications are still important tasks for the researchers and engineers in the field of FTCS [49,53,54,206]. From theoretical point of view, unified, systematic theory and design techniques are waiting for developing. From practical engineering application point of view, efforts in redundancy management, fault propagation and reliability analysis, integrated design for AFTCS, as well as practical engineering implementation in conjunction with redundant hardware and software structure are important problems for future research.

With the rapid advance in microelectronics and mechatronics techniques, intelligent actuators and sensors possessing self-diagnostic properties are available [21] [242–244]. These intelligent instrumentations will have significant impact to the overall structure how to design and implement FTCS in a more cost-effective and reliable way. Those built-in diagnostic behaviors should be fully exploited in AFTCS design.

On the other hand, the rapid extension 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 limitation of the existing FTCS. Most of the existing development in AFTCS focused mainly on algorithmic design which takes into little consideration on system's overall architecture and technical platform used or to be used. New technologies for integrated designs of the entire FTCS together with associated implementation platforms (hardware, software and communication protocol) are desired, both from the practical and theoretical point of view [147,50,201] [164,141,245,246].

Overall, fault-tolerant control is a complex interdisciplinary research field that covers a wide and diverse range of engineering and science areas, such as system modeling 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. FTCS have also very wide application areas including many safety-critical, life-critical, and mission-critical engineering systems in aerospace engineering, electrical, computer, and software engineering, mechanical and manufacturing engineering, chemical and petrochemical engineering, power engineering, transportation engineering, medical and biomedical engineering etc. For developing practical FTCS, FDD schemes and reconfigurable controllers should be designed in conjunction with techniques in fault-tolerant/reconfigurable computing, communication networks, software [194,247,238]; fault tolerant real-time/embedded systems [248–250]; advances in sensors and actuators [243,244,21]; advances in microelectronics and advanced electronic devices such as FPGAs; and hardware/software co-design and implementation. In this regard, not only reconfigurable/ restructurable controller and FDD design techniques themselves, but also techniques relating to real-time stability and reliability analysis, and real-time computing, communication, and reconfigurable hardware/ software implementation have to be considered as a whole in the design of functional FTCS.

6. CONCLUSIONS

As a new emerging area in automatic control, fault tolerant control has attracted more and more attention in recent years. A brief review and the associated bibliography on the historical and new development in active fault-tolerant control systems (AFTCS) has been presented in this paper. The existing approaches in fault detection and diagnosis (FDD) and reconfigurable control (RC) are outlined with emphasis on the RC design techniques. Several open problems and current research topics in designing AFTCS have been discussed and 250 references have been cited. Since FTCS cover such wide disciplines and due to the limitation of space, many existing publications cannot be included although most of journal papers and some of conference papers have been listed.

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