A Detail of Fault Tolerant Flight Control Techniques

Jayalakshmi M, Vijay. V. Patel, Giresh. K. Singh

Abstract*: *Fault tolerant flight control (FTFC) system deals with the detection and diagnosis of faults and looks at the task of regaining control in the presence of the fault. Current modern aircraft are made highly complex for comfort or high performance. The study of improvement in safety, redundancy, and adapting the flight control laws after its occurrence of faults has fascinated the thoughtfulness of several investigators in the previous two decades. Overall illustration of different fault diagnosis and fault-tolerant flight control approaches involved are provided in this review paper.

Keywords: **Control, Fault-tolerant, Fault-detection, Aircraft**

I. INTRODUCTION

Most commercial and military aircraft are controlled by flight control systems (FCS) which are capable of suppressing undesirable effects produced as a result of turbulence, noise. However, the FCS must handle the unwanted failures in sensors, actuators, control surfaces. Modification or Adaptation of Control law is essential to improve the aircraft response after failure effects. In real-time after fault or failure, this modification or adaptation of control law must be done in short period. All aspects of safety, reliability, availability, maintainability of FCS must be considered after fault/failure. Hardware redundancy is termed as the machinery backup tools used to escape the damage of system's functions effectiveness. The analysis methods are to be considered to explore the effects of faults on the system reliability and safety in the design phase. Failures cannot be avoided completely even after assuring quality control carried out while manufacturing or using reliability and safety analysis methods carried out during the design and testing. Hence, fault tolerant design is needed to compensate the faults that do not lead to system failures. This need has led to the development of the concept of the FTFC scheme which is composed of monitoring, detection, diagnosis, and reconfiguration methods that modifies the control law to the plant [1].

The following are some of the instances that inspired the requirement of fault tolerant flight control system. In the incident of flight L-1011 in 1977 described by Montoya et.al (1983) [2], the pilot took 3.5 minutes to recuperate the aircraft with his efforts, and was able to land the aircraft safely. Another incident of the DHL Airbus A300B4-203F freighter [1] that was hit by a surface to- air missile, lost the hydraulic power , control surfaces (elevators, ailerons, spoilers and rudder) were frozen, and went drooping as their actuators exhausted, trailing in the slipstream, entered into phugoid motion. The crew finally made a successful landing. Recent Lion Air 610 crash report [3] indicated that AoA sensor was not calibrated properly. Maneuvering Characteristics Augmentation System (MCAS) of flight read the wrong sensor values of angle of attack made the plane push down the nose to prevent from going to stall.

A failure classification of the accidents involving commercial jet airplanes worldwide from 2006-2017 is shown in Fig.1 [4]. It shows that the in-flight loss of control was major lethal accident group. A recent paper [5] on the loss of aircraft briefed about the research in advances for comprehensive solution to LOC under extensive range of hazards briefed by researchers and National Aeronautics and Space Administration (NASA). LOC Problem Analysis Methodology of full accident/incident set, and an analysis of accidents and incidents is given by Christopher et.al (2010) [1], Fabio et. al (2009) [2], Belcastro et. al (2010) [6] and in [7].

The fault tolerance schemes can be put up together using Redundancies, Voting techniques, Performance monitoring, Redundancy management, Pre-flight tests, and Asynchronous operation of flight control system. The use of redundant hardware back-up methods [7] will enhance volume, weight and cost forfeitures to the aircraft. Redundant sensors are considerably less expensive to fix than actuators. Redundant architectures can increase aircraft's maintenance time because of rise in quantity of parts and difficulty. Fault tolerant flight control systems (FTFC) are termed as the systems that are failure tolerant and increased survival of aircraft by utilizing flight control systems. The primary required feature of the FTFC system is to decrease loss in controllability, and to sustain scheme to control securely without danger to equipment loss and to people.

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II. ELEMENTS OF FTFC

FTFC systems are generally separated into two classes: passive and active. Passive FTFC Systems are systems built on robust controller design techniques that make the closed-loop system insensitive to anticipated faults. This methodology is computationally attractive as it needs no online detection of the faults. The active FTFC systems need a fault detection and diagnosis (FDD)/ fault detection and identification (FDI) scheme to identify and localize faults when they that has the task of detecting and localizing the faults if they happen in system. The reconfiguration mechanism (RM) modifies the parameters and/or the controller structure to achieve suitable post-fault system performance from information of estimated faults as shown in Fig.2. Many control approaches are available to achieve FTFC.

Active FTFC systems are of two types. Projection-based active system accounts for only a subcategory of faults like passive systems. In this method, controller selection is established on predetermined controller and individual controller is considered aimed at a precise fault condition which is detected by FDD. In Online redesign active systems, controller parameters are recalculated and hence called as reconfigurable control systems. These approaches are extreme computationally challenging as they have the greatest performance.

The disadvantage of passive systems is that they are conservative, designed to handle a certain disturbance set with the fault tolerant controller based on robust control techniques, and can quite often masks failures. The drawbacks of active control include complexity of control laws, false alarms, and non-detection delays.

A. Latest Advancements In FDI

The major challenge in designing for fault tolerance is incorporating a suitable fault detection and identification (FDI) scheme. Qualitative and quantitative modeling tools regarding many fault scenarios are available as FDI is established area of study, for e.g. Patton (1997) [2]. The FDI unit is an important segment of the active FTFC system. Patton [2] acknowledged that when fault happens, FDI system has the capability to collect data about the changes happening in the parameters of the system or in the system operating point. FDI scheme is built on the assumption that with the occurrence of fault, the physical limits change and hence the plant model dynamics also changes. The maximum investigated approaches [8] in FDI part are the residual generation observers approaches like Kalman filter, Multiple Model Filters, Unscented Kalman Filter. Robustness issues in FDI are critical as false fault indications can happen because of mismatches in the model of the plant.

According to Belcastro (2010) [2], Fault detection is divided into three classifications.

i) Signal processing fault detection methods work with characteristics of spectrum signal information or statistical information to allow generation of signals which indicates the failure occurrence.

ii) Knowledge-based methods use techniques of artificial intelligence techniques such as neural networks (NNs) or fuzzy-logic to identify and categorize faults.

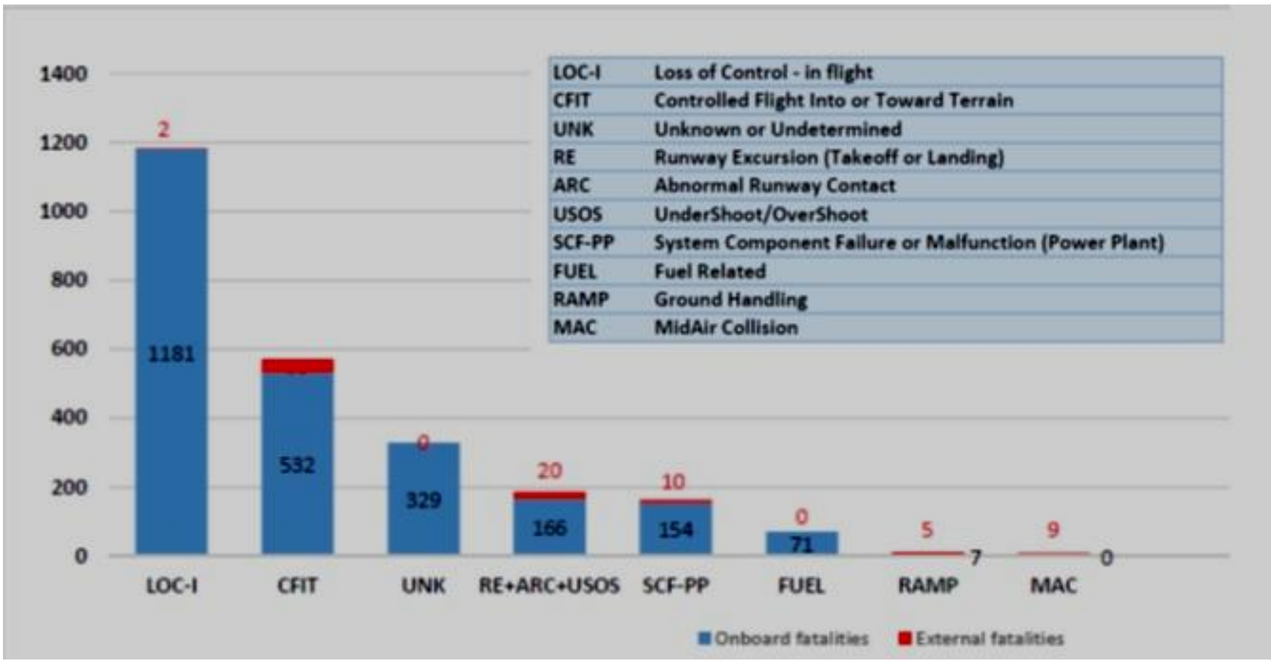

Fig. 1: Accident statistics and fatalaties categories by CICTT avitation for worldwide commercial jet aircrafts, 2009-2018 [4]

Courtesy: https://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf

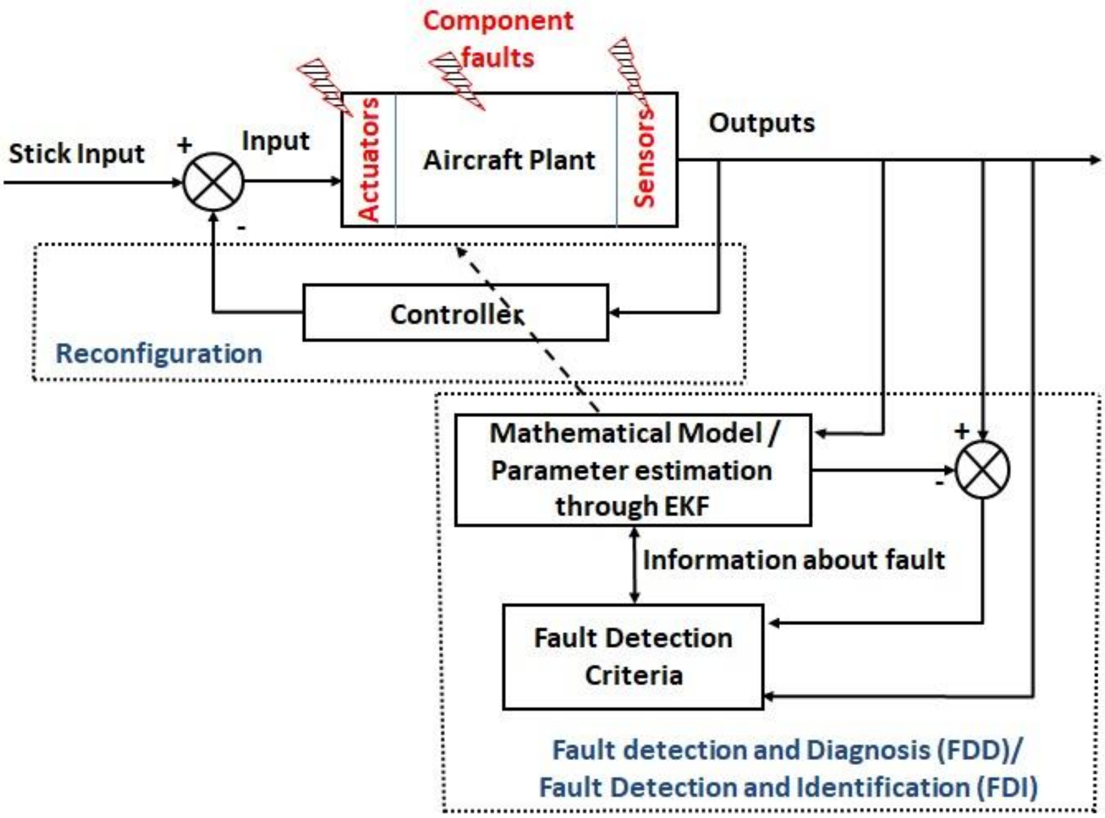

Fig. 2: Active FTFC system

iii) Model-based methods are related to signal processing methods excluding the model which is used to measure the error signals that detects the presence of failure. The number of false alarms can be reduced by improving the performance and reliability of fault detection and isolation.

Some of the FDI schemes are given below

- One of the active FTFC design which comprises of Unscented Kalman Observation Filter for FDI and model predictive controller for FTFC was explained in [9].
- Comparison of various machine learning FDI techniques to identify aircraft faults are described in [10]. Aircraft failures of engine, elevator, flaps and aileron are demonstrated in SIVOR, Motion-based flight simulator.
- Failure detection was based on fuzzy-genetic algorithm was explained in [11]. Time of incidence and type of different actuator failure was estimated by Fuzzy-based classifier. An optimal fuzzy rule set for the classifier was generated by Genetic algorithms. Nonlinear simulations with various actuator failures of F-16 aircraft are discussed
- A Neural network based sensor fault detection scheme was explained by Lennon et. al (2016) [6] provides onboard sensors analytical redundancy (AR) on UAV
- From the notions of bio immune systems modeling with artificial intelligence (AI) techniques, FDI scheme was presented by Mario (2010) [6] that was able to detect and recognize actuators failures, and sensors.
- An observer-based adaptive algorithm of fault estimation given by Jianwei et. al (2016) [6] was applied for F-16 aircraft linear model system with actuator faults. Sudden changes in correlation of pitching, yawing and rolling moments are utilized for the detection of the fault in FDI.
- The FDI method of Multiple model switching and tuning (MMST) explained by Jovan et. al (2010) [6] was implemented to a linearized aircraft model of air and space vehicle which can handle moderate uncertainty and tolerate small set of failures. In model predictive control multiple model-based methods [6] different models referred to identification models are used to identify and define the current system dynamics for different operating regimes.
- Aircraft FDI system composed of an adaptive observer and a bias estimation algorithm was projected for the stuck fault detection of aircraft multiple control surfaces [12]. Adaptive observer FDI algorithm and control allocation method was explained in [12] for fault detection of stuck control surfaces. Simulations have shown that the proposed FDI algorithm to improve the performance of the responses after the fault.
- Aircraft fault signal was estimated by using the sliding mode methods of FDI module which described in [13]. Sliding mode state feedback was implemented successfully and evaluated on Group of Aeronautical Research and Technology in Europe (GARTEUR) flight simulator and discussed in [13]. Finite time system trajectories were reached along the sliding mode surface with the proposed sliding mode observer FTFC scheme.
- Intelligent flight control system was proposed for unmanned aerial vehicles that can be tolerant to faults of actuator [14]. This FDI can detect and automatically accommodate the faults using neural networks. Simulations have proven that with the proposed system has stable flight with the fault of actuator.

- The FDI was based on the extended multiple model adaptive estimation (EMMAE) explained by Guillaume (2009) [6] and [15] which can work on all probable actuator locked positions or floating positions. A group of extended Kalman filters are intended to observe the actuator health, and allows estimation of the fault control signal by the respective EKF. The results shown that EMMAE method were capable to detect faults of various types.

B. Latest Advancements In FTFC

- Reconfigurable fault tolerant flight control (RFTFC) was introduced to provide accommodations for failures of in-flight and to increase safety based on the motivation of research on several aircraft accidents. Most of the current reconfigurable control systems are developed with the assumption of perfect information from the FDI system [1, 16]. The different mathematical control approaches usually used for FTFC with their drawbacks are listed in Table I

Table- I: Control approaches of FTFC

Methods [1]	Remarks
Control Allocation(CA) by Federico et.al (2011) [6] Linear /Nonlinear: Both Active/Passive: Active	For reconfiguration, control allocation (CA) requires information on the health of all actuators, information to identify a fault and allocate control authority. Drawback: The system was not guaranteed to remain stable if actuator limitations and dynamics are not considered into account.
Sliding mode control (SMC) [17] Linear /Nonlinear: Nonlinear Active/Passive: Both	The order of the dynamic model of the plant is reduced and convergence of the discontinuous control law occurs in a limited time. Drawback: Implementation imperfections lead to chattering
Dynamic Inversion DI (or Feedback linearization) [18] Linear /Nonlinear: Nonlinear Active/Passive: Both	Simple nonlinear design and guarantees asymptotic stability for the error dynamics and system Drawback: Inverse dynamics incorporating the full flight envelope has to be calculated and no guarantee on existence of the matrix inverse used for control law and stability of internal dynamics
Robust control by Ian et. al (2005) [6] Linear /Nonlinear: Linear Active/Passive: Passive	$H\infty$ method applied to multivariable systems. Drawback: Requires reasonably good system model to be handled and constraints such as saturation are not controlled properly.
Adaptive Control [19] Linear /Nonlinear: Linear Active/Passive: Active	Ability to improve itself given unexpected circumstances. Drawback: Robustness was not guaranteed against high-frequency un-modelled dynamics and noise.
Linear matrix Inequality(LMI) [20] Linear /Nonlinear: Nonlinear Active/Passive: Both	LMIs are an effective tool for solving optimization and control problems Drawback: Difficult to write the problem in terms of linear matrix inequalities (LMIs) set.
Model Predictive Control (MPC) ([1] and Fabio et. al (2009) [6]) Linear /Nonlinear: Both Active/Passive: Both	Inherent fault tolerant properties Drawback: Requirement of an accurate model and online optimization was computationally demanding
Linear quadratic regulator (LQR) by Bin. et. al (2013)[6] Linear /Nonlinear: Linear Active/Passive: Both	Attention needed on control inputs amplitude and state variables settling time. Drawback: Constraints not easily integrated
Intelligent control (Pashilkar et. al (2006) [6] Linear /Nonlinear: Nonlinear Active/Passive: Both	Easily applied to nonlinear systems. Drawback: Artificial neural network (ANN) involves the weights adjustment on-line that can necessitate tuning in various flight regimes.
Pseudo Inverse Method [21] Linear /Nonlinear: Linear Active/Passive: Active	Simplicity in computation and implementation. Drawback: No guarantee on the stability of the damaged system
Gain scheduling GS and linear parameter varying [22] Linear /Nonlinear: Nonlinear Active/Passive: Active	The basic idea was to design local linear controllers by linearization of nonlinear system at operation points. Computational burden is less than other nonl Drawback: Too many operating points are needed for effective controller
Multiple Model [23] Linear /Nonlinear: Nonlinear Active/Passive: Active	Time to fault alertness can be decreased. Drawback: More models are used for characterizing different fault scenarios. Control action provided will not be optimal when the current model which was active does not characterize the current state of system
Linear model Following [24] Linear /Nonlinear: Linear Active/Passive: Passive	Simple control structure with only the constant gains in the feedforward and feedback path. Drawback: severe constraints required on the reference model
Eigen structure Assignment [25] Linear/Nonlinear: Linear Active/Passive: Active	Ability to recover the eigenvalues of the pre-fault closed-loop system completely. Drawback: Achievable eigen values and eigenvectors may not allow the system to recover.

III. FTFC RESEARCH METHODOLOGIES

Abundant research work has happened in fault tolerant flight control area in the past decade (references). A few of the major FTFC research programs are briefly discussed below.

- The fault tolerant real-time control strategies were assessed by European Flight Mechanics Action Group (FM-AG (16). This group developed the 6-Dof Flight simulator, SImulation MOtion and NAvigation (SIMONA) described by Halim et.al (2009) [6] and [26] was used to assess the FTFC tools in real-time. Novel FTFC techniques were assessed in the environment by using some realistic scenarios of actual past failure cases in flight simulator and results shown that FTFC was successful in improvement of handling qualities performance. Research on FTFC scheme containing sliding mode control (SMC) and control allocation (CA) approach which can deal directly actuator failures with redundant actuators was commenced by

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the FM-AG (16) group Halim et.al (2008) [6]. An adaptive nonlinear dynamic inversion approach of FTFC was also formulated and done in FM-AG (16) discussed by Halim Alwi et.al (2009) [6]. Based on data from digital flight data recorder of the B747 Flight 1862 accident, GARTEUR developed a simulation benchmark (RECOVER). The benchmark [1] was used extensively in offline design, implementation and analysis of new FTFC algorithms in simulations as realistic as possible.

- According to Perhinschi et. al (2004, 2006) [6] , [27] and [28], NASA developed FCS which was intelligent to cater for control surface failures and for different fault scenarios on F-15 aircraft. Nonlinear dynamic inversion augmented with a neural network (NN) based FTFC scheme [29] was used to compensate aircraft fault dynamics caused by control surface failure. The simulations were conducted with different fault scenarios of canard and Stabilator. Results shown that EMRAN helped in reducing angular rate tracking error. Self-learning neural networks using adaptive flight control technology about accommodation of unanticipated failures. Simulations with adaptive FTFC have shown that there was an improvement of pitch response and reduction of tendency of pilot-induced roll oscillation with failure of stabilator.
- Adaptive neural network-based reconfigurable control design methods [30] were explored by the program of Reconfigurable Control for Tailless Aircraft (RESTORE).
- Simulations evaluated on ADMIRE (the Aero Data Model in Research Environment) with an active FTFC of reallocation scheme using optimal control law, based on pseudo inverse method (PIM) without reconfiguring the baseline controller described by Sijun et. al (2010) [6] after fault has occurred.
- Linear parameter varying (LPV) FTFC control synthesis method explained by Jong et.al (2007) [6] were designed using gain scheduling concept and applied on a civil transport aircraft. Both passive and active controllers and the effect of time delays were investigated. Controllability was not guaranteed in the active FTFC for fault detection delay times greater than ten seconds. The passive controller used the stabilizer and elevator for control in healthy conditions where only elevator was used.
- The flight test evaluations capability in LOC conditions i.e., the operational and safety procedures developed for Air STAR operations [5,7] have turned out to be the gold standard for subscale vehicle flight testing.
- An active FTFC design method was able to identify the fault by accounting degraded performance through degraded reference model which was tested on F-8 aircraft model. Eigen structure Assignment (EA) algorithm described by Youmin Zhang et. al (2003) [6] automatically designs the controller once fault was detected.
- FTFC using Sliding mode control (SMC) by Halim et. al (2008) [6] was simulated for both sensor and actuator faults on Boeing 747 civil aircraft model. The state feedback controller gain with sliding mode control scheme was allowed to adaptively increase, when the fault was sensed.
- Simulations of aircraft actuator faults are demonstrated with passive FTFC [31] adaptive SMC gain by Lyapunov stability theorem that confirms closed-loop stability. Results have revealed that adaptive SMC fault tolerant controller does better than conventional SMC controller. Model following based SMC described by Zhi-jun et. al (2009) [6] was also tried to confirm that sliding mode had dynamic properties and to make zero steady-state error.
- Multiple Model approaches are one of the widely used methods for FTFC in predicting faults described by Jovan Boskovic et.al (2010) [6]. A decentralized FDI and reconfigurable adaptive control scheme active FTFC were implemented on F/A-18A aircraft model. This scheme has direct adaptive controller that uses estimates of the parameters from each observer using MM switching, and can control multiple simultaneous faults.
- Adaptive Control techniques explained by J.D. Boskovic et. al (2007) [6] were designed and tested on simulations F/A-18 aircraft by giving high- frequency signals for actuators with suspected failures. The method guaranteed convergence of the failure parameter estimates to true values.
- It was demonstrated that fault tolerance obtained with blending aerodynamic and propulsion actuation clarified by Moshe et.al (2001) [6] assisted the flight operation safely with failure of actuator. The evaluation of proposed FTFC of on-line learning neural networks based adaptive control strategy and actuator reallocation schemes for actuator failures was also demonstrated in nonlinear simulation environment
- Using optimization methods, an optimal gain design procedure was explained by Abderrazak et.al (2000) [6] that can tolerate control system failure with acceptable handling qualities. This method was demonstrated on F/A-18 model with known set of failures.
- Model reference adaptive control [32] was used as the basis for FTFC and applied to a model of the F/A-18A aircraft. Failure simulations with three adaptive controllers simple MRAC, without a disturbance estimation adaptive Law (onMRAC), with a disturbance estimation adaptive law (onMRAC+) controllers were demonstrated for frozen left stabilator, roll input to pitch coupling, reduced roll and pitch damping. The degraded aircraft performance was significantly improved with all adaptive controllers.
- A multiple-model method was demonstrated in [33] for selection of control strategy under failures of engine actuation, failures of air data sensors and multiple simultaneous sensors failures. Computer simulations of the generic transport model (GTM) with stable adaptive controller demonstrating system stability are also illustrated for the above said failures.
- Linear quadratic regulator (LQR) design clarified by Bogdan et.al (2006) [6] for FTFC was done with the Boeing 747 short-period longitudinal model Newton-Raphson based fault accommodation algorithm was used for solving AREs to redesign controller which was used for the post fault model actuator faults.
- Simulations were shown on a F-16 model with both active-passive FTFC method merging SMC with adaptive

control described by Afef (2009) [6]. In this technique, the nominal controller was based on sliding mode methodology. If the state of system changes outside a given boundary and if system performance degrades with the actuator fault, then the adaptive controller output was added to nominal controller output.

- Another Active –passive method with LMI based nominal controller was discussed by Xiang et.al(2006) [6]. Simulations of both linear and nonlinear studies have shown that with appropriate FDD information, the active system worked better than passive system.
- The FTFC approach of Smart Adaptive Flight Effective Cue system was integrated with the model following system in the Calspan Learjet in-flight simulator [34]. Evaluation of quantitative performance assessments showed that pilot induced oscillations tendencies were reduced, which could otherwise lead to a loss of control.
- L1 adaptive control formulation was presented in [35] for bi proper reference systems and output uncertainties. Simulation results provided evidence of the benefits of this system for avoiding and mitigating loss-of-control scenarios in aircraft with un-modeled dynamics, system damage, and external disturbances

IV. FTFC RESEARCH METHODOLOGIES ON UAV

- An active FTFC system for UAV was described by Francois et.al (2007) [6] to deal with FDI approach using signal processing methods and linear quadratic controllers to handle the failures of the control surfaces.
- The Re-allocation of the healthy actuators was stated as problem of optimization with equality, inequality constraints controller design was based on EA as decribed by Francois Bateman et. al (2008) [6].The algorithm explained in this paper gives new functioning trim point of the defective linearized model that remains near the fault-free model.
- The nonlinear flight control systems (FCS) for an UAV with saturation of actuator and unknown disturbances are represented by Takagi-Sugeno fuzzy models as explained in [36]. Simulations have proven that adaptive fault tolerant tracking controller was effective to recover from the fault problem of actuator loss of effectiveness.
- The FTFC approach of DK-iteration adaptation algorithm has shown guaranteed stable robust system performance [37]. The algorithm was verified in simulation environment of fixed-wing unmanned aerial system (UAS) and in real-flight experiments with an UAS.
- Simulation results are presented on a generic 6DoF nonlinear aircraft model [38] with FTFC comprising of a nominal controller and an NN based adaptive controller. At a time, separation principle of the time-scale was utilized to control both the outer-loop states which are slow and inner-loop states which are fast.
- Numerical simulations with 22% of right wing loss and 25% loss for both vertical tail and rudder control surfaces of blended wing body (BWB) aircraft were conducted [39]. Results have proven that MRAC [39] as reconfigurable FCS have shown good performance.
- The damage-tolerant control (DTC) technology described by Damien et.al [6] in Rockwell Collins was intended to alleviate UAV failures like damages of engine failure, airframe, control surfaces. The MRAC method was able to recover the baseline controller of a subscale F-18 UAV after losing actuation. Automatic supervisory adaptive control (ASAC) made the aircraft back to controllable after disastrous wing damage within seconds and made effective autonomous landing.

V. RESULTS AND ANALYSIS OF FTFC METHODS

In this paper, various methods from literature were presented for the study of fault tolerant flight control system. The typical automatic landing controller results with failure of one surface control surface and thereby decrease in control surface effectiveness of F-16 aircraft is provided in this paper. The decrease of control surface effectiveness may occur due to bird hit or battle damage. The mathematical model was employed in MATLAB- Simulink environment. The reconfiguration with the principles of nonlinear dynamic inversion, fast and slow separation states, control allocation and sliding mode methods after estimation of the decrease in control surface effectiveness was used for the simulation. The simulation result of the automatic landing controller [40] with decrease of 90% left aileron control surface effectiveness is provided in Fig. 3. The simulation result shows that the controller helps to land safely.

Based on the study and analysis of different methods available literature in fault tolerant flight control system area, comparison is carried out in Table 2. These methods are tried as simulation study by most of the researchers. Therefore, at present lot of confidence is available, at least to try on various scaled flying models in order to get more practical data.

Table II: Comparison of control reconfiguration methods tested in the area of FTFC

Control Reconfiguration Method	FDI model incorporated into the model	Can handle Actuator failure	Can handle Structural failure
Model Reference Adaptive Control	Yes	Partial loss of actuator failure, Not Complete	Yes
Model Predictive Control	Yes and also with assumed fault model	Yes	Yes
Eigen structure Assignment	Assumed fault model	-	Yes
Sliding Mode Control	Assumed fault model	Partial loss of actuator failure, Not Complete	Yes
Dynamic inversion	Yes and also with assumed fault model	Yes	Yes
Psuedo inverse method	Assumed fault model	-	Yes
Control allocation	Assumed fault model	Yes	-

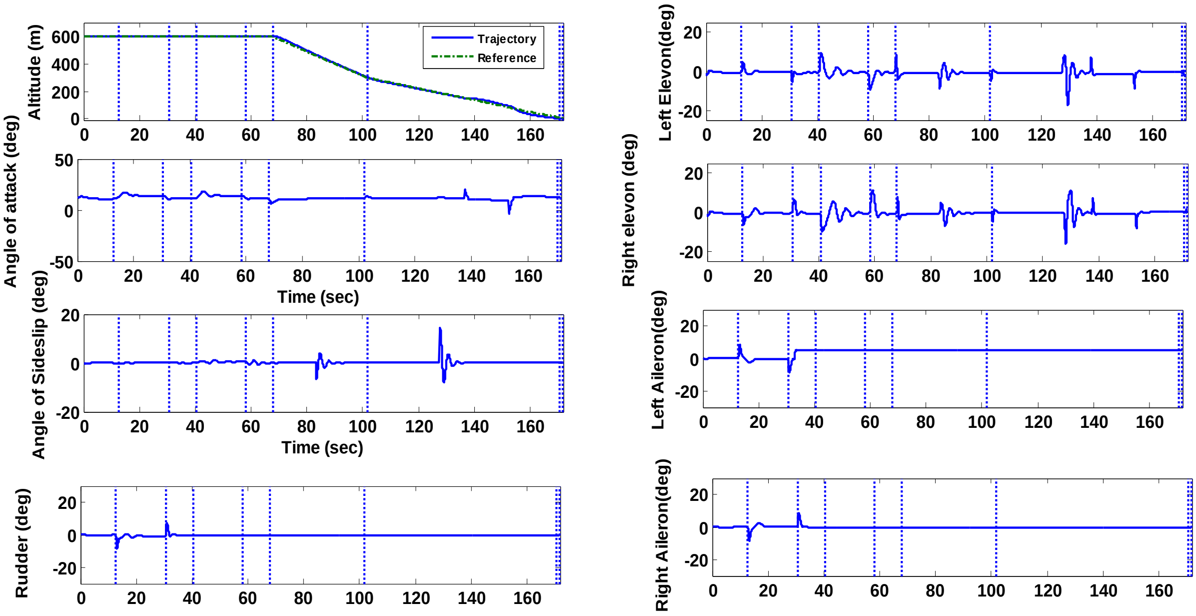

Fig.3 Simulation responses with automatic landing controller [40] with -5 deg stuck left aileron and 90% left aileron surface effectiveness drop

VI. CONCLUDING REMARKS IN FTFC RESEARCH METHODOLOGIES

The advancements in Vehicle Dynamics Modelling and Simulation for LOC effects [1, 41-43] resulting from external disturbances and vehicle damage placed the source for generation of realistic multiple hazard LOC scenarios. Significant advancement was already made in real-time system identification technologies [1,44-45] that can identify the modifications in system motion and features of control in LOC dangers in unfavorable conditions (e.g., vehicle damage) and extreme flight stall/departure conditions [46].

FTFC systems are not being readily approved by aerospace industry, in spite of various methods that have been explored. The contributing factors of FTFC system for not being accepted are the complexity of the FTFC design, the probability of false alarms because of modeling uncertainties. The technology readiness level for FTFC system needs to be improved since flight control system is safety-critical. Nonlinear adaptive techniques needs to be evolved from linear based design control systems used in expansion of flight envelope especially for UAV's as they are increasing demand by the military.

VII. CONCLUSIONS

In this review paper, numerous fault detection and fault tolerant control techniques associated with flight were discussed. The reviewed FDI techniques disclose that fault detection and estimation can be used successfully for determining the actuator, control surface or sensor faults in aircraft. Likewise, the fault associated scenarios can be improved by FTFC techniques. Evaluation of performance through high-fidelity simulations and flight tests are the further probable upcoming directions in this area. Research on predictive methods for safety assurance in real-time is essential for future safety-critical independent systems and developments in aeronautics and aviation. Confirmation of these approaches need a synchronized approach involving real-time monitoring, advanced simulations, and experimental testing. Novel methods are required for assessment and quantification of the confidence level in the process of validation and results. Innovative methodologies are also essential for verification of stochastic and complex systems

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