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Review on Fault Detection and Fault Tolerant Control Applied to Flight

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Abstract: ***In the field of fault analysis of various systems, the fault design comprises of mainly two research streams, one is called fault detection and isolation (FDI) which deals with the detection and diagnosis of faults that occur in a controlled system, and the other called fault tolerant control (FTC) that looks at the task of achieving control for countering the fault. The high complexity of modern systems makes them vulnerable to almost any fault such as sudden breakdown or malfunction of a sensor or an actuator. Therefore, in order to improve the operational safety and system redundancy, reducing the possibility of such failures or predicting it before its occurrence is imperative. This review paper presents different fault detection and control strategies involved in flight.***

Keywords: Fault Detection and Isolation (FDI), Fault Tolerant Control (FTC), Kalman Filter, Multiple Models

1. Introduction

"A fault is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition."[1]. Based on this definition, a fault may correspond to any unusual behaviour of a system, which may not affect the general system functioning but may eventually lead to failure. A fault can be small or hidden, and hence, difficult to detect and identify. "A failure is a permanent interruption of a system's ability to perform a required function under specified operating conditions."[1] Resulting from one or more faults, a failure is therefore an event that can terminate the functioning of a unit in the system. On an aircraft, actuators are used for deflection of control surfaces such as ailerons, elevators, and rudders, and also to operate the engine throttle and the landing-gear mechanism. An actuator is declared failed when it cannot be controlled any longer. The reconfigurable flight control system is capable of not only detecting faults in the system but is also able to adequately compensate for such failures (which is more difficult than to only accommodate faults).

2. Fault Detection and Isolation System

Detection and isolation of faults in complex plants is one of the most important tasks assigned to the system that supervises the plant. The early detection of faults can help in avoiding major catastrophes, ones that could otherwise result in damage of materials. Fault detection is very important for systems such as airplanes, industrial plants, nuclear power plants and space vehicles. In the case of airplanes, if an actuator or a control surface fails to function as required, the vehicle may become uncontrollable. Similarly, if a sensor fails to present correct data, it can cause incorrect action of an actuator that can lead to instability. Thus, the timely detection of various kinds of faults is essential for ensuring the safety of the system.

2.1 Building Blocks of FDI Systems

This section deals with the different types of possible building blocks for the development of a benchmark FDI system.

2.1.1 Kalman Filter

The Kalman filter, also known as linear quadratic estimator (LQE), is an algorithm that uses a set of measurements observed over time, which may contain noise (random variations) and other inaccuracies, and correspondingly produces estimates of unknown variables that tend to be more precise than those based on a single measurement alone. The Kalman filter basically operates recursively on streams of noisy input data to produce a statistically optimal estimate of the considered system state. The major drawback of using the Kalman filter is that it can only perform state estimation for linear systems. This is crucial as almost all systems in nature are nonlinear. Also, the Kalman filter provides low accuracy on tracking for higher order systems.

2.2.2 Extended Kalman Filter

The Extended Kalman filter (EKF) is the nonlinear version of the Kalman filter which linearizes about an estimate of the current mean and covariance. In case of well-defined transition models, the EKF has been considered as the standard in the theory of nonlinear state estimation of navigation systems and GPS. The extended Kalman filter works by the principle of linearizing the signal model about the current state estimate and using the linear Kalman filter to predict the next estimate. This attempts to produce a locally optimal filter, however, it is not necessarily stable. In addition, if the initial estimate of the state is wrong, or if the process is modelled incorrectly, the filter may quickly diverge, owing to its linearization.

2.2.3 Unscented Kalman Filter

The Unscented Kalman Filter differs from the extended Kalman filter by avoiding linearization of the nonlinear system. This is achieved by the use of unscented transform. The Unscented Transform (UT) replaces the mean vector and its associated error covariance matrix with a special set of points with the same mean and covariance. In other words, instead of having to derive a linearized approximation, the equations could simply be applied to each of the points as if it were the true state of the target. This reduces the computational effort required for estimation. Hence inaccuracies developed due to linearization are avoided.

2.2.4 Particle Filter

During the 1990s, the particle filter (PF) was well known in the field of recursive nonlinear state estimation, and has been widely applied in many fields (see e.g. (Gordon and al. [31], Bolviken and al. [32], Doucet and al. [33], Benhmida and al. [34]). The PF solves the Bayesian recursive relations by using Sequential Monte Carlo (SMC) methods. These methods allow for a complete representation of the posteriori probability density function of the states, so that any statistical estimates, such as the Minimum Mean Squared Error estimate (MMSE) and the Maximum a Posteriori Probabilities (MAP) can easily be computed. In year 2000, Kadirkamanathan and al. [35] introduced Sequential Monte Carlo methods in the field of fault detection and isolation (FDI). Because the PF is able to handle any functional nonlinearity as well as system or measurement noise of any probability distribution, it has attracted attention in the nonlinear non-Gaussian state estimation field.

2.2 Fault Detection and Isolation Techniques

2.2.1 FDI Using Multiple Model Based Adaptive Estimation (MMAE) Schemes

One approach to detect and isolate actuator or sensor faults is the multiple model adaptive estimation (MMAE) method [9]. It uses a bank of Kalman filters (KF) running in parallel, each of which is matching a particular fault status of the system. The next step is the use of a hypothesis testing algorithm by which the residuals from each KF is assigned a conditional probability for each fault scenario. It is evident that the computational load is quite intense. Thus the online use of this method was impractical for quite a long time. However, as time passed, more powerful processors where available making this method regain appeal in many applications. Several papers demonstrated how the MMAE method can be used in the context of fault detection and isolation for aircraft [10], [11], [12] and underwater vehicles [13]. The MMAE method will have reliable practical application as long as the expected faults can be hypothesized by a reasonable number of Kalman filters.

However, the major disadvantage is associated with the fact that the number of addressable faults is limited due to the computational load required for each filter.

2.2.2 FDI Using Extended Multiple Model Based Adaptive Estimation (EMMAE) Schemes

In order to make the MMAE method acceptable for any flight conditions and also capable of isolating lock-in-place or floating actuator faults, the MMAE algorithm is combined with Extended Kalman filters (EKF) which are capable of carrying out nonlinear estimation of some (unknown) fault parameter like the deflection of a faulty control surface (or actuator). The resulting method is called “Extended Multiple Model Adaptive Estimation” (EMMAE), [29], [30]. The EMMAE enables online estimation of the deflection of a faulty actuator to cope with lock-in-place or floating actuator fault scenarios and drastically reduces the number of filters needed.

3. Fault Tolerant Control System

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

3.1 Passive Fault Tolerant Controllers

In a passive fault-tolerant controller, when the plant parameters deviate from their true values or that of the actuators from their expected position, it may be efficiently compensated by a fixed robust feedback controller. However, if these deviations become excessively large and exceed the robustness properties, some actions are needed to be taken. Also, if deviations occur at the sensor side, inevitable deviations from the reference command signals will happen. Therefore, an active fault-tolerant control architecture is needed in order to achieve extended fault-tolerance capability and is thus preferred over passive controllers.

3.2 Active Fault Tolerant Controllers

An active fault-tolerant controller usually contains two separate modules. One module is basically a fault detection and isolation (FDI) system that monitors the health of the aircraft. The FDI system then informs the second module which is a supervision module, regarding the seriousness of the fault/failure or damage. Based thereon, the supervision module may decide to reconfigure the flight controllers, the guidance system, and the navigation system.

There are two families of FDI systems, namely passive FDI and active FDI systems. Passive FDI systems “wait” until something starts to clearly go wrong in the system [2], whereas the active FDI systems will artificially excite the aircraft, either by flying health check maneuvers [3], [4] or by injecting test signals [5], [6] in the actuator commands and then assessing the individual health status of actuators and sensors.

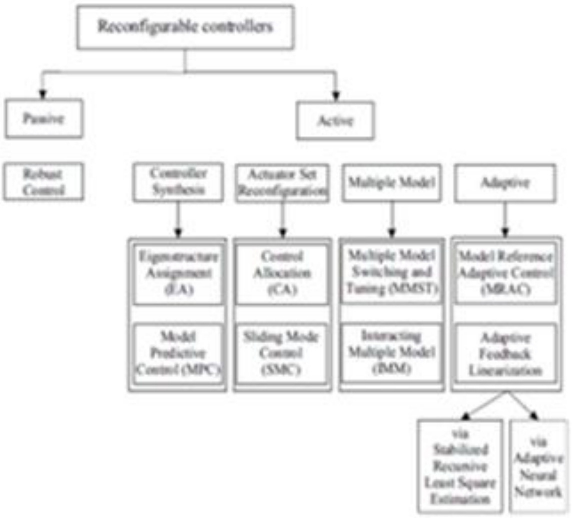

Figure 1: Fault Tolerant Control Schemes

4. Different Approaches for Fault Tolerant Control

The figure above, summarizes the most common techniques used in reconfigurable flight control systems. The mentioned techniques are explained below.

4.1 Multiple Model Techniques

4.1.1 Multiple Model Switching and Tuning (MMST)

In the MMST technique, the dynamics of each fault scenario are described by a dedicated model. Each model is also paired with its respective controller. When a fault occurs, the control system is reconfigured by choosing the model/controller pair that is the most appropriate at each time step. The MMST technique has the advantages of being fast and usually stable if the actually occurring failures match the predefined fault scenarios. However, severe limitations of the method arises in practice as soon as an unmodeled failure is encountered or if multiple or structural failures occur. Moreover, the number of individual pairs of model/controller to be designed may become excessively large if the system is to successfully operated over a wide range of failure scenarios [8], [7].

4.1.2 Multiple Model Adaptive Estimation (MMAE)

Another approach to detect and isolate actuator or sensor faults is the multiple model adaptive estimation (MMAE) method [9]. This method belongs to the family of Interacting Multiple Models (IMM). It is based on a bank of Kalman filters (KF) running in parallel, each of which is matching a particular fault status of the system. A hypothesis testing algorithm then uses the residuals from each KF to assign a conditional probability to each fault hypothesis. As one may expect, the computational load is quite intense. Therefore, the online use of this method was impractical for a long time. However, with the more powerful processors now available this method has regained appeal in many applications.

Several papers have demonstrated how the MMAE method can be used in the context of fault detection and isolation and control reconfiguration for aircraft [10], [11], [12] and underwater vehicles [13].

4.2 Control Allocation Techniques

Control allocation techniques can be briefly stated by the following general relation, the flight control system generates a virtual control command CV = [CL CM CN] T in terms of the desired roll, pitch, and yaw torques. This virtual command CV is passed to the control allocator which is provided for each actuator's position limits and effectiveness to produce any torque component of the CV vector. An algorithm is then computed online to optimally generate control signals for the actuators [14], [15], [16].

The major advantage of using a control allocation technique is that actuator failures can be compensated for without the need for modifying the flight control laws [17]. Moreover, actuator's constraints, such as deflection limits and motion rates, can be taken into account by the control allocator (CA) when the virtual command CV is "distributed" over the actuators. Finally, the deflection of each actuator can be chosen by the CA to optimize some criteria, such as total drag, total deflections, or to prioritize some actuators. However, as explained in [7], control allocation techniques may have the following possible disadvantage: "the dynamics and limitations of the actuators after a failure are not taken into account in the control laws." This means that the controller will still attempt to achieve the original system performance even though the actuators are not capable of achieving it.

4.3 Model Reference Adaptive Control

Model reference adaptive control [18], [19] is a method which can be utilized when tolerance to damage or structural failures is required. This technique is also often used as a final stage of a complex control system combining several algorithms. The working principle of this type of control is to have the output of the plant under consideration to follow the output of a reference model. However, the Model Reference Adaptive Control (MRAC) technique has some limitations. Firstly, the adaptation laws require an estimation algorithm to track certain parameters of the system. It is therefore necessary that these system parameters evolve slowly enough in order that the estimation routine can track them properly. Faults or failures, however, may cause abrupt changes in the values of the system parameters. Secondly, during the transient phase in which the adaptive algorithm identifies the new faulty plant; it is not guaranteed that the controller can stabilize the system. Therefore, the model reference adaptive control technique is usually not used on its own but in combination with other algorithms in a more complicated fault-tolerant control architecture [20], [21].

4.4 Other Reconfigurable Control Methods

There are other methods to design a reconfigurable flight control system. For instance, the Eigen structure assignment (EA) is used to reconfigure the feedback control laws in [22] and [23]. In Model Predictive Control (MPC), the constraints on actuators or on any other state variables are systematically taken into account during the generation of the control signals [24]. Sliding Mode Control (SMC) has been investigated in [25] or more recently in [13], [26], and [27]. Other reconfigurable flight control systems use adaptive feedback linearization via artificial neural network (ANN) [28] or via online parameter identification methods [20].

5. Conclusion

In this review paper, various fault detection and fault tolerant control techniques associated with flight were discussed. The reviewed FDI techniques reveal that model based fault detection and estimation can be used successfully for determining the actuator, control surface or sensor faults in aircrafts. Similarly, the FTC techniques proved to be sophisticated when they are used as a combination of several algorithms to improve the fault associated scenario. These techniques, both FDI and FTC for aircrafts can be applied to space vehicles like launch vehicles, spacecraft and reusable launch vehicles. This is mainly due to the fact that they follow the same dynamics of flight when they make reentry into the Earth’s atmosphere.

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