Reconfigurable Flight Controller for the STOL F-15 with Sensor/Actuator Failures

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ABSTRACT
A multiple model adaptive controller that provides for reconfiguration in response to sensor and/or actuator failures is developed for an approach and landing profile for the Short Take-Off and Landing (STOL) F-15 aircraft. Each elemental controller within the multiple model controller is based on a Command Generator Tracker/Proportional plus Integral/Kalman Filter (CGT/PI/KF) design, with residual monitoring used as the mechanism to select the appropriate controller. The elemental controllers are each based on an assumed system status: no failures or a single failed surface or sensor. Controller selection is evaluated for controller mixing based on all algorithm-computed probabilities of each elemental controller being the “correct” controller to use. The entire multiple model controller is evaluated against a truth model with a single failure, and then repeating the process for all failure modes of interest.

INTRODUCTION
More than ever, modern aircraft are depending on the capabilities of the flight control system to provide controllable flight. This is especially true in the case of fighter and other special purpose aircraft which may not exhibit static stability. It is therefore highly desirable to have a flight control system which can maintain an aircraft at a commanded attitude and trajectory despite the existence of sensor or actuator failures. One approach to developing such a flight control system is the multiple model adaptive controller (MMAC) [1,2].

The basic premise is that a controller designed for a specific design point should perform better than one that is not. In previous research [3-8] a single controller was made as robust as possible to encompass off-design conditions. The trade-off was increased controller coverage versus performance at the primary design point (Figure 1). The multiple model adaptive controller on the other hand allows a controller for the primary design point as well as secondary design points (Figure 2). These controllers can then be tuned for better performance at their design points than one all-encompassing controller.

Figure 1. Failure Coverage of a Single, Robust Controller

Figure 2. Failure Coverage of the Multiple Model Adaptive Controller

The essence of the multiple model adaptive controller is to combine several elemental controllers, each designed for a particular aircraft status, with an adaptation mechanism. The adaptation mechanism then selects, based on the aircraft’s current status, the most appropriate elemental controller, or blending of elemental controllers, to have authority over the aircraft. For the multiple model adaptive controller configuration reviewed here, the adaptation mechanism...
mechanism is based on residual monitoring. The residual data is produced by comparing measured data with predicted values of measurements generated by a Kalman filter embedded in each elemental controller. The adaptation mechanism assigns probabilities to each elemental controller based on how closely the residual characteristics match their respective anticipated values. The probabilities are then used to weight the control authority of each elemental controller in order to form the adaptive control vector for the system.

Other issues also drive the practical implementation of the multiple model adaptive controller in flight control applications. One is the availability of control surfaces which can exert authority in other than their primary axis. An example is the use of differential horizontal stabilators to supplement roll control. A failure in an aileron can thus be covered by an elemental controller designed to use more differential stabilator.

The other technology driving an actual flight control implementation of the multiple model adaptive controller is computer system architecture. As the multiple model adaptive controller's name implies, there are several elemental controllers running simultaneously. For real-time operation, this would dictate a parallel, or multi-processing, architecture for the host computer. Fortunately, research has already addressed how to create fault-tolerant, multi-processing computer systems for flight critical applications [9-11].

MULTIPLE MODEL ADAPTIVE CONTROLLER

The multiple model adaptive controller developed for this study, as depicted in Figure 3, is based on the multiple model adaptive filter [2,12]. Although they produce two distinctly different results, the probability computations for each are identical. The probability of the k-th elemental controller (k = 1,2, ... K) being correct, given a time history of measurements through time t, can be computed recursively via [12]:

\[
p_k(t^i) = \frac{\int_{\mathbb{R}^n} f_{Z}(t^i|a(Z(t^i-1)|a, Z(t^i-1)) f_{Z}(t^i)|a, Z(t^i-1)) \prod_{j=1}^{K} \int_{\mathbb{R}^n} f_{Z}(t^i)|a(Z(t^i-1)|a, Z(t^i-1)) f_{Z}(t^i)|a, Z(t^i-1)) p_j(t^i-1) \prod_{j=1}^{K} \int_{\mathbb{R}^n} f_{Z}(t^i)|a(Z(t^i-1)|a, Z(t^i-1)) f_{Z}(t^i)|a, Z(t^i-1)) p_j(t^i-1)}{\sum_{j=1}^{K} \int_{\mathbb{R}^n} f_{Z}(t^i)|a(Z(t^i-1)|a, Z(t^i-1)) f_{Z}(t^i)|a, Z(t^i-1)) p_j(t^i-1) \prod_{j=1}^{K} \int_{\mathbb{R}^n} f_{Z}(t^i)|a(Z(t^i-1)|a, Z(t^i-1)) f_{Z}(t^i)|a, Z(t^i-1)) p_j(t^i-1) \prod_{j=1}^{K} \int_{\mathbb{R}^n} f_{Z}(t^i)|a(Z(t^i-1)|a, Z(t^i-1)) f_{Z}(t^i)|a, Z(t^i-1)) p_j(t^i-1)}
\]

where K represents the total number of elemental controllers to be considered. Obviously the individual probabilities at any time step must be greater than or equal to zero, and their sum equal to one.

The density function shown in the numerator of (1) is given by [12]:

\[
f_{Z}(t^i|a, Z(t^i-1)|a, Z(t^i-1)) = \frac{1}{(2\pi)^{m/2}|A_{k}(t)|^{1/2}} \exp\left\{-\frac{1}{2} r_{k}(t^i)^{T} A_{k}^{-1}(t) r_{k}(t^i)\right\}
\]

where \(A_{k}(t^i)\) is the residual covariance generated by the Kalman filter in the k-th elemental controller and is given by:

\[
A_{k}(t^i) = H_{k}(t^i)|a \hat{X}_{k}(t^i)^{T} H_{k}(t^i) + R_{k}(t^i)
\]

and \(r_{k}(t^i)\) is the computed residual for the same controller, namely:

\[
r_{k}(t^i) = Z(t^i) - H_{k}(t^i) \hat{X}_{k}(t^i)
\]

To prevent a controller from being "locked-out" because its associated probability has gone to zero (a consequence of the numerator of (1)), a small lower bound should be placed on the computed elemental probabilities. This lower bound restraint has two purposes with regard to preventing a zero probability. First, an elemental controller's probability may temporarily equal essentially zero before reaching a nonzero steady state value while the controller converges on the correct solution. The second is for handling sequential failures. If an elemental controller's probability is allowed to go to zero, thus keeping it there for all time, the multiple model adaptive controller algorithm may "miss" a subsequent failure for which that elemental controller was designed. Since a total probability of greater than one does not make sense, a rescaling of the probabilities will have to be performed in order to accommodate these lower bounds.

As the adaptation mechanism depends on the similarity of the computed residual covariance (3) and the actual residual charac-
teristics in order for the algorithm to operate correctly, care must be taken during the filter tuning process. The addition of too much pseudonoise can mask the difference between "correct" versus "incorrect" models within the filters and thus between residuals produced by such filters. The residuals from the "correct" model ought to have much better characteristics as compared to those from "incorrect" models.

ELEMENTAL CONTROLLER DESIGN

The elemental controllers of the multiple model adaptive controller in this study are of the Command Generator Tracker / Proportional plus Integral/ Kalman Filter (CGT/PI/KF) form. One controller is designed for each of the specified failure modes using Linear system, Quadratic cost, and Gaussian noise model (LQG) synthesis. Controllers are established for the following conditions: healthy aircraft, failed stabilator, failed pseudo-surface, and failed pitch rate sensor. The pseudo-surface is a combination of the canard, aileron, and trailing edge flap [1,3].

The CGT/PI/KF controller was chosen mainly on the basis that it had an embedded Kalman filter and had been used with success in a prior study [3]. Notwithstanding, other features of the CGT/PI/KF controller make it a desirable controller to use for flight controller. The command generator tracker (CGT) portion of the controller is an explicit model follower which forces the aircraft states to track desired trajectories. It is through the CGT that the desired handling qualities of the aircraft are actually incorporated.

In order to be able to hold a nonzero equilibrium condition despite a zero error signal and unmodelled disturbances (characteristics of a "type-1" controller) a Proportional plus Integral controller is combined with the CGT. The ability to reject constant, unmodelled disturbances is important as the aircraft may not be operating at the exact point which was used to generate the linear perturbation model used for the design. Also incorporated is implicit model following, to penalize deviations from the desired system transient response of a desired closed loop system, thereby enhancing the ability to produce controllers with good pole placement, loop shapes, and robustness properties.

The Kalman filter portion of the CGT/PI/KF controller serves two functions in the elemental controllers. First, it provides estimates of all the states based on noise corrupted sensor data to facilitate use of full-state feedback controller design. Additionally it provides the residuals required by the adaptation mechanism in the multiple model adaptive controller. Although Loop Transfer Recovery (LTR) [13] could be applied to enhance the elemental controller's robustness, it is purposely ignored in favor of not incapacitating the adaptation mechanism since LTR tuning tends to mask the difference between filters based on "good" versus "bad" models.

The operating point for which the elemental controllers were designed was the landing phase of the STOL F-15 aircraft. The aircraft was considered to be operating at sea level with a speed of 200 feet per second and a nominal weight of 33,576 pounds. The variables chosen for states of the controller were velocity, angle of attack, pitch, and pitch rate.

All the elemental controllers were designed under the assumption that the system was time invariant in nature. This allowed constant filter and controller gains to be employed in order to reduce computational requirements. The actuator failures were simulated by zeroing the appropriate column of the control input matrix. In a similar fashion, a sensor failure was simulated by zeroing its row in the measurement matrix. Based on these assumptions and simulations, all the elemental controllers had very similar responses when compared against their higher order truth models. Representative of the results is the response of the healthy aircraft commanded to a negative five degree (-0.873 radian) flight path angle depicted in Figure 4.

Figure 4. Typical Elemental Controller Performance (healthy aircraft shown)
MMAC EVALUATION

The multiple model adaptive controller utilizing the elemental controller design of the previous section was evaluated for the four design cases (healthy aircraft, failed stabilator, failed pseudo-surface, and failed pitch rate sensor). In each case, the full complement of four elemental controllers was evaluated against a truth model representing the healthy aircraft or one of the modelled failures. As discussed in the section on the multiple model adaptive controller, a lower bound on the computed hypothesis probabilities was defined at 0.01 to prevent "lock-out". In all evaluation runs, the elemental controller representing the healthy aircraft was initially given a probability of 0.85, forcing the others to values of 0.05 each. This represents a realistic scenario as the aircraft is assumed initially to be healthy and then is impaired by a failure.

The plots presented in Figures 5 through 8 display the multiple model adaptive controller response to operating on an aircraft with no failures, failed pitch rate sensor, failed stabilator, and failed pseudo-surface respectively. In each case, the maneuver is the same negative five degree commanded flight path angle used to evaluate the individual elemental controllers (Figure 4). For each figure, plot (a) presents the controlled variables of interest, and plot (b) displays the probability time histories for each elemental controller.

For the cases of a healthy aircraft and one with a failed pitch rate sensor, Figures 5 and 6, the multiple model adaptive controller almost immediately selects the correct controller. The probability plots for each case, Figures 5-b and 6-b, show the probability of the correct controller in each case reaches approximately 0.97 which is the upper limit dictated by the forced lower bound of 0.01. The controlled variable plots (Figures 5-a and 6-a) show well behaved responses similar to that of Figure 4. The evaluation of the failed stabilator case presented in Figure 7 indicates the multiple model adaptive controller exhibited some indecision before arriving at the correct solution. As can be seen in Figure 7-b, the controller oscillates for approximately a second between the elemental controller for the healthy aircraft and the one for the failed stabilator. Despite the initial indecision, the controlled variable plot (Figure 7-a) indicates the desired flight path angle was achieved, albeit delayed by one second.

Evaluating the multiple model adaptive controller against an aircraft with a failed pseudo-surface actuator produced results very much different from those obtained in the other three tests (Figure 8). The probability plot (Figure 8-b) indicates that the controller has difficulty in determining which elemental controller to weight most heavily, and in fact settles incorrectly on the one designed for the failed pitch rate sensor case. Further inspection of the plot reveals the probability for the failed pseudo-surface actuator elemental controller barely moves from the lower bound of 0.01. This indicates that the characteristics for the residuals associated with the failed pitch rate sensor controller are in much better agreement with their internally computed

(a) Controlled Variables
(b) Elemental Controller Probabilities

Figure 5. Aircraft with No Failures
Figure 6. Aircraft with Failed Pitch Rate Sensor

Figure 7. Aircraft with Failed Stabilator

Figure 8. Aircraft with Failed Pseudo-Surface
covariance ($\Lambda_k$) then are those for the failed pseudo-surface. Based on the incorrect control being applied, it is of little surprise that Figure 8-a displays divergent behavior. It is interesting to note, however, that the elemental controller for the healthy aircraft yields acceptable performance for the case of a failed pseudo-surface actuator (Figure 9). This indicates the healthy aircraft elemental controller is robust enough to handle that particular situation.

Two solutions to the mis-identification problem present themselves immediately. The first would be to retune the Kalman filters associated with the failed pitch rate sensor and failed pseudo-surface actuator elemental controllers. This approach could be further supplemented with additional residual testing or other fault detecting mechanisms. The other approach is to remove the failed pseudo-surface actuator elemental controller entirely and let the one for the healthy aircraft handle the case of a failed pseudo-surface actuator. Of course some filter retuning is likely in this latter case as Figure 8-b indicates the two most probable elemental controllers are for the cases of a healthy aircraft and a failed pitch rate sensor.

Overall, the multiple model adaptive controller based on a bank of four elemental controllers exhibited good performance in the test cases investigated. Three additional elemental controllers were designed for the cases of failed velocity sensor, failed flight path angle sensor, and failed reverser vane (for pitch control) cases during the period of research. Unfortunately, although good closed loop performance was achieved, the inclusion of any in the multiple model adaptive controller bank caused the simulation software consistently to terminate prematurely due to numerical difficulties.

SUMMARY
A reconfigurable flight controller, based on multiple model adaptive controller techniques, has been designed for the STOL F-15 and exhibits effective performance in response to sensor and actuator failures. Of the test cases evaluated (healthy aircraft, failed stabilator, failed pseudo-surface, and failed pitch rate sensor), only the failed pseudo-surface case had undesirable results. Possible causes for the poor performance in that particular case have been identified, as well as potential solutions.

The multiple model adaptive controller capitalizes on the inherent qualities of the Command Generator Tracker/Proportional-plus-Integral/Kalman Filter (CGT/PI/KF) controller, most notably the state estimates and residuals of the Kalman filter, to select a controller which can provide positive trajectory control over an aircraft with an actuator or sensor impairment. This selection process is achieved through comparison of the elemental controllers' (each individually tailored to a given impairment condition) predicted values of measurements and the measured outputs from sensors. The elemental controller with the smallest residual values (relative to the filter-computed residual covariance, i.e., the smallest magnitude of quadratic in Equation (2)) is considered the best candidate to exert the desired control over the aircraft.

This research explored only single total failures of actuators or sensors. Further research is required into the multiple model adaptive controller's performance in the face of partial failures, and identifying various actuator failure modes (i.e. free-floating, locked at neutral, and locked at stop). The case of sequential failures must also be addressed.

Although the multiple model adaptive controller approach is proven as a possible design technique for adaptive flight control systems, one major shortcoming does exist. The computational power required to realize the multiple model adaptive controller, especially in light of its highly parallel structure, precludes practical implementation in existing flight control systems. This, however, should not dissuade further research into the use of the multiple
model adaptive controller in advanced flight control systems.

As is implied in the previous paragraph, the development of the multiple model adaptive controller will depend in part on research in other areas. The computational aspect mentioned is only one issue related to the host flight control computer. Another is the computer's ability to detect and recover from its own faults. In order for the multiple model adaptive controller to be a viable flight controller for high performance aircraft, it must be hosted on a computer system which has a high degree of availability. Making the aircraft tolerant of failures and not the computer system hosting the adaptation algorithms is rather self-defeating. Fortunately, computer systems with increased computational capacity and fault tolerant capabilities are undergoing substantial development.

Another area which deserves further investigation is the aerodynamic cross-coupling of control surfaces. For any type of adaptive control system to be successful, it must be able to replace the control power lost from a failed surface with excess control power available from another surface. Redundant surfaces are one approach, but more might be gained from more specialized surfaces such as independently controllable flaps and horizontal stabilators, thrust vectoring nozzles, and canards. By no means is this list of surfaces complete, but it does provide a point from which to start.

As can be seen, the multiple model adaptive controller is a promising technique in solving part of the overall flight control problem. Continued research in this area, as well allied areas, promises to yield even greater advances in the area of advanced flight control technologies.

BIBLIOGRAPHY


