

FAULT DETECTION OF A FLIGHT CONTROL COMPUTER IN A HARSH ELECTROMAGNETIC ENVIRONMENT

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Abstract

Verifying functional integrity of flight control computers(FCC) in harsh electromagnetic environments is a key issue in development, certification, and operation of systems performing flight critical functions. A strategy is being developed for real-time detection of control command errors caused by electromagnetic environments in FCCs during validation testing. A system level approach to FCC fault detection and mitigation in real time is proposed. Monitoring the health of the FCC based on analysis of simplex flight path data is proposed. This data will be collected during nominal closed loop tests of an AlliedSignal quad-redundant FCC interfaced to an emulation of the aircraft engines, sensors, and actuators, and running B737 Autoland control laws. Each flight is the aircraft landing during disturbances associated with wind gusts. Sensor inputs and command outputs for every frame will be stored for each flight. System Identification techniques will be applied to the data to approximate non-linear models for the commands. With the FCC subjected to a High Intensity Radiated Fields (HIRF) environment, multiple landings of the aircraft will be performed, and on-line estimates of the commands will be calculated using the nominal models. A statistical analysis will be performed to characterize the density functions of the estimation errors for both upset detection thresholds and for determination of the probability of missed detections and probability of false alarms. Once the threshold data has been determined, the FCC will again be subjected to a HIRF environment. The difference between the estimated and FCC commands, and the thresholds, will be used to determine if an upset has occurred. A plan is proposed so that in the event that the FCC is malfunctioning, the aircraft can be flown based on the estimated command signals rather than on the command signals generated by the upset FCC.

Introduction

Monitoring of the control commands of the B737 Flight Control Computer (FCC) can be used to produce an early detection of system faults. The purpose here is to detect failures before they have a devastating effect on the performance of the aircraft. The health-monitoring scheme proposed in this paper assumes proper functioning of all sensors and uses these sensor measurements to produce an estimate of the correct control command. The estimated control command is compared to the FCC calculated control command and the difference is used to determine if an upset has occurred. The FCC used in this experiment is quad redundant, however it can be viewed as a signal system by using the voted values of the four processors to produce a single command. The health monitor predicts this voted command based on the sensor measurements and a model of the FCC. A comparison is then made between the measured command signal and the estimated command single for real-time upset detection. The region of interest in this study is restricted from glide-slope engaged to flare, which is the region of the Autolander.

Modeling And Analysis Of The Throttle Command Of A 737 Flight Control Computer

This section presents the modeling of the throttle command calculated by a Flight Control Computer (FCC) using the B737 Autoland flight control laws. The control laws were implemented on a quad redundant Allied Signal FCC. The FCC was then placed in closed loop with a B737 simulator. The simulator accepted elevator, throttle, aileron, and rudder control commands from the FCC and sent simulated sensor commands to the FCC. A block diagram is shown in figure 1. The simulated approach includes atmospheric disturbances, such as winds and gusts.

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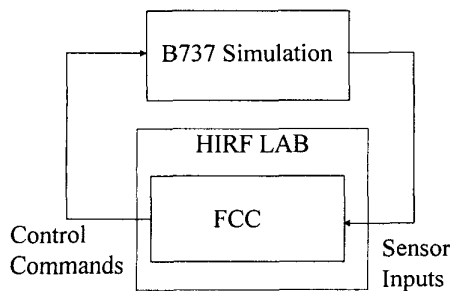


Figure 1. Block Diagram of FCC Test System

In this section, attention is focused on the throttle command over the region from glide slope engaged to flare. The goal is to develop a mathematical model of the throttle command given the input sensor measurements. This is done in order to compute real-time estimates of the throttle

command during flights with random winds and gusts. This estimated throttle command is then compared to the measured throttle command and the difference, or residual, is used for upset detection.

The computations of the control commands by the FCC are nonlinear due to the voting, asynchronous sampling, nonlinear nature of the control laws, and mode switches within the FCC. By limiting the valid range of the throttle model from glide slope engaged to flare, most of the difficulties caused by mode switching can be avoided. The nonlinear nature of the control laws can be approximated by a set of linear control laws that can be modeled using standard state space system identification techniques cascaded with nonlinear functions. Once the nonlinearities are identified, the measured input and output data can be preprocessed to form a linear state space model from input to output. The resulting representation for the throttle command is shown in figure 2.

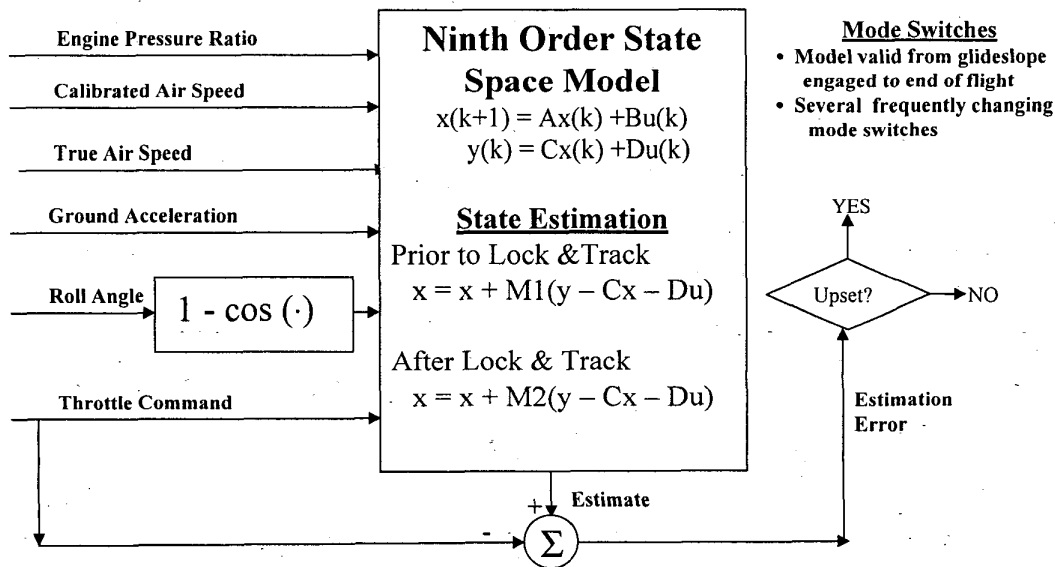


Figure 2. System Diagram of Throttle Command Estimator

A linear model based on the preprocessed data can be formed using any system identification technique such as batch least squares or observer Kalman identification (OKID). The resulting state space model is shown in Eq. (1).

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned} \quad (1)$$

In this equation, x is the state, u is the preprocessed sensor measurement, and A , B , C , and D comprises the state space model. The model of Eq. (1) requires an estimate of the state. While OKID returns the optimal state observer, the Quadratic Linear Estimator (LQE) method will be used since the goal of the FCC model is upset detection. In the LQE formulation, the user is to determine an observer gain based on how much to trust the sensor measurements versus how much to trust the plant output measurements given the process noise variance and the measurement noise variance. For upset detection, it is assumed that a reliable state estimation cannot be based on command measurements since such a measurement may be corrupted. So the detection process demands an observer that highly trusts the input measurements and views the plant output measurements with a great deal of suspicion. However, an initial knowledge of the correct state is essential in FCC command output estimation. In order to achieve this, an aggressive observer that trusts both command and sensor measurements is used for the first few frames of data to lock on to the correct state. Once this is done, the aggressive observer is replaced with a weak observer which relies very lightly on the command measurements which results in a state space model with a good estimate of the initial state several frames after glide slope engaged and is suitable for upset detection. This scheme is presented below in figure 3.

If frame number is the first few frames after glide slope engaged:

$$x(k) = x(k-1) + M_1 (y(k) - Ax(k) - Bu(k))$$

If frame number is beyond first few frames after glide slope engaged

$$x(k) = x(k-1) + M_2 (y(k) - Ax(k) - Bu(k))$$

Figure 3. Observer Selection Scheme

Here, M_1 is the aggressive observer that relies greatly on the command measurement to lock on to the initial state and M_2 is a weak observer.

The system modeling technique is applied to the throttle command that results in an estimation scheme that can be used for throttle command modeling. In order to produce a linear model that is valid for any given run of the closed loop system of Figure 1, several runs are made with random wind gusts. The runs used here all were for the case of 6ft/sec wind gusts. Changing the seed of the simulator random wind model can produce statistically different runs. The input and output data for the FCC obtained from several runs is used to construct the state space model by updating the covariance matrix of each new batch as described in [1]. The resulting model generalizes for the given sets of data and can be thought of as an approximate linear model for the throttle command of the FCC when cascaded with the nonlinear prefilter. In figure 4, we see the throttle command produced by the FCC as the solid line and the output of the estimator as the dotted line for a representative case. Figure 5 is the estimator error for this nominal case. Note that the model was developed for the portion of the flight regime from glide slope engaged to flare, which occurs between data frames 900 and 3200. Outside of this regime, the estimator model has not been developed yet, so the estimation error is large, and the detector cannot be applied.

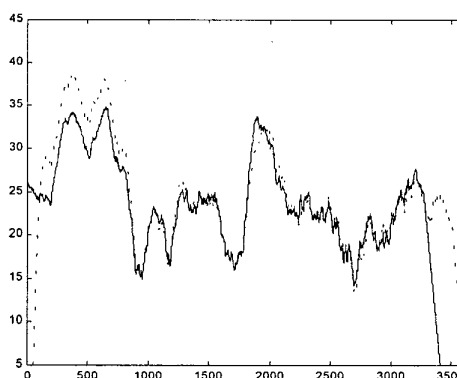


Figure 4. Tracker Output & FCC Output, No RF case

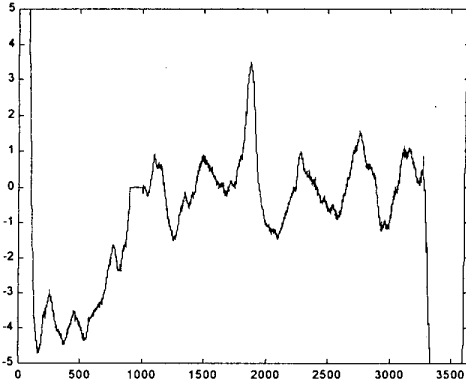


Figure 5. Tracking Error, No RF case

The above figures show the tracking capability of the state space observer. The figures are for the case when no Radio Frequency, (RF) disturbance is present. As can be seen, the tracking algorithm generalizes and produces little error in the No RF case for glide slope engaged to flare. The tracking error can be approximated by a normal distribution based on the mean and variance of the tracking errors for the No RF case. This probability distribution will be used with the distribution resulting from the RF On case to set a threshold for upset detection.

It is the goal of the tracker to detect upsets due to RF. When the FCC is placed in the High Intensity Radiated Fields (HIRF) chamber shown in Figure 1, the plot of figure 6 results. This plot resulted from RF settings of 560 V/meter and at a frequency of 200 MHz. As can be seen in the figure, the FCC failed to provide the proper throttle command. This failure resulted in an unsuccessful landing for this flight. The tracking error is shown in figure 7.

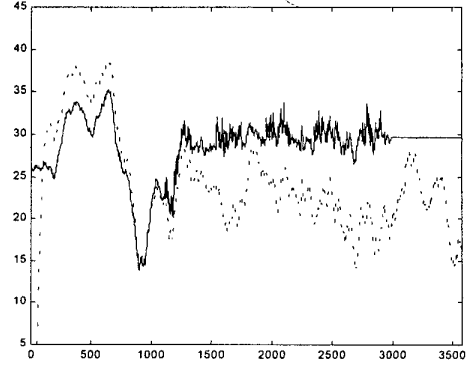


Figure 6. Tracker Output & FCC Output, RF On

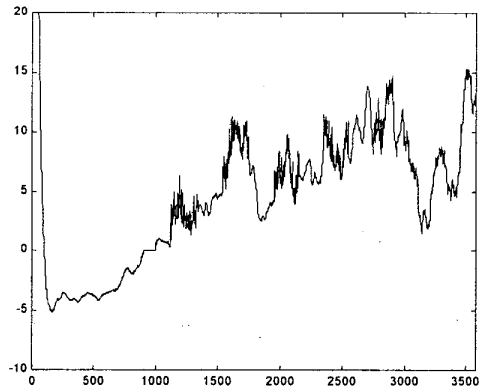


Figure 7. Tracking Error, RF On

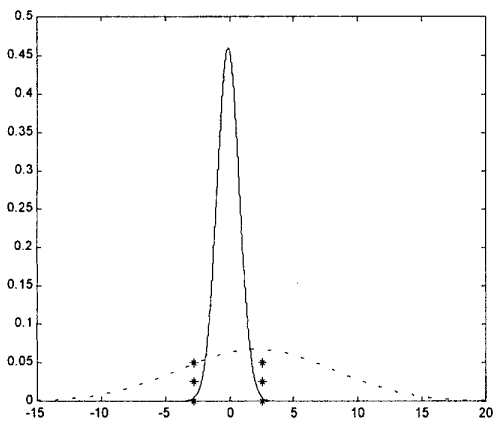
The tracking error shown in figure 7 can be used to form a statistical base of the error distribution. This statistical base results from performing the RF test several times for different simulations of winds and gusts and different levels and frequencies of RF. However, the database contains only those runs that resulted in an upset. This is done to determine the mean and variance of the upset FCC command in order to incorporate the data into the detection algorithm.

Both the RF On and No RF sets of data may be used to form a statistical base for an upset decision rule. This rule will be based on the assumption that the tracking errors are normal distributions and that the data available is a fair representation of the system performance. Table 1 shows the mean and variance for the No RF and RF On cases.

Table 1

	No RF	RF On
Mean	-0.10490	2.1065
Variance	0.75180	35.049

The values shown in Table 1 were determined by using the tracker error from several flight cases. For the No RF case, five runs were performed with wind gust of 6 ft/sec having different seeds for the random wind simulation. The tracking errors were then used to calculate the mean and variance for the normal distribution. For the RF On case, ten runs that caused a FCC upset were used with different levels of RF and different frequencies to determine the mean and variance of the tracking error. The probability density functions for both cases are shown in Figure 8.

**Figure 8. Probability Density Functions for Upset Detection**

In Figure 8, the solid line is the No RF case and the dotted line is the RF On case. The two lines of asterisks mark the decision thresholds that are set at -2.7755 and 2.5657 . The decision rule is simple; any error less than -2.7755 or greater than 2.5657 is considered an upset. When this decision rule is used, the detection probabilities shown in Table 2 result [2].

Table 2. Probabilities

<i>Probability of False Alarm</i>	<i>0.002</i>
<i>Probability of Detection</i>	<i>0.6742</i>

The detection scheme here is for a single frame of data. Even though the probability of detection is fairly low, it is assumed that the detection of an upset is not critically dependent on doing so in the first frame after upset. This gives the detector several frames after upset to determine that an upset has occurred while avoiding false alarms.

Conclusion

The above detection algorithm can be used for the upset detection of the B737 Autoland FCC. This scheme was applied to the voted output of a quad-redundant FCC executing B737 Autoland commands. Although this paper presents data for the throttle command only, this scheme can also be applied to the other Autoland commands – aileron, elevator, and rudder. Future work includes extending the detection scheme and demonstrating real-time detectors for all commands in the laboratory. Possible extensions to the detection scheme include multi-dimensional decision rules, detection filters, decision fusion, and multi-level detection that would include monitors for each channel as well as for the voted output. Finally, additional experiments will be performed that involve various RF conditions, winds and gusts, and voting schemes for the FCC.

References

1. Juang, J.-N., "System Realization Using Information Matrix", *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 3, May-June 1997.
2. Cooper, G. R., and McGillem, C.D., *Probabilistic Methods of Signal and System Analysis.*, New York: Holt, Rinehart and Winston, 1986, pp. 64-79.