Robust Fault Diagnosis for Fixed Wing Aircraft Fault Tolerant Flight Control System

R. Jaganraj, R. Velu

Abstract: ***Fault Tolerant Flight Control (FTFC) system and Fault Detection and Identification system (FDI) are used to isolate the aircraft fault and recover its operation during the fault occurrence. FTFC and FDI uses either actuator feedback or desired performance monitoring method to estimate fault source. These methods are limited with the fault source identification. FTFC and FDI have limitation in identification of the fault source. FTFC and FDI needs to be revisited with respect to the identification of fault source. This paper presents the design and implementation of FTFC based on a robust model reference fault detection and identification system (MRFDI) for fixed-wing aircraft. The proposed method demonstrates the identification of actuator fault, measurement error in instrument and presence of uncontrolled disturbance. The proposed method combines the actuator feedback with aircraft parameter to distinguish faults in actuator, instrument and deviation due to uncontrolled motion of the aircraft. A typical aircraft mathematical model of the aircraft is simulated with developed FTFC embedded with MRFDI. The fault is injected to simulate actuator fault, feedback instrument fault and uncontrolled motion to observe the performance of FTFC. Results reveals that proposed FTFC method is distinguishing different fault sources among them and recovering aircraft from fault occurrence.***

Keywords – Model Reference Fault detection and identification system, Fault tolerant flight control, fault classification

I. INTRODUCTION

FTFC is used to recover the faulty aircraft during the occurrence of fault. FTFCs are classified as active and passive based on the application of FDI in the FTFC. Active FTFC consist of additional FDI scheme to estimate fault and operate whereas passive FTFC operates without FDI. Most of the FTFC are functioning without FDI and employ a combination of different control methods. FTFC is developed by comparing achieved and demanded aircraft altitude [1]. Authors applied FTFC on twin engine unmanned aircraft and successfully recovered faulty aircraft for predefined fault scenario. It was also explained that the absence of FDI limits the functionality of FTFC. The damaged aircraft is experimented in a wind tunnel to identify the parameters during physical damage of the aircraft. [2], [3]. Authors developed FTFC based on the reallocation of normal dynamical model to the faulty dynamical model for flight control. FTFC is developed by replacing faulty actuator with trim actuator to control the altitude of the commercial aircraft model [4]. The fault scenario executed is malfunction of primary elevator. Authors identified fault from actuator feedback and replaced control to the trim actuator during the fault occurrence in elevator actuator. FTFC is developed by incorporating twin actuator configuration as primary elevator and secondary trim control in [5]. Uncertainty and disturbance estimator (UDE) is developed to identify fault by authors. Authors tested their FTFC for actuator fault and uncertain fault. They also explained that the system assumed deviation in performance as the environmental uncertainty, if the fault was not found in primary actuator. FTFC is classified into active control and passive control [6] and [7]. The passive FTFC requires fault detection, identification and control reconfiguration, whereas, the active method reacts to demands (faults) actively by reconfigurable control scheme. FTFC is developed by combining LQR (linear quadratic regulator) and MARC (Model reference adaptive control) [8]. Damaged aircraft dynamics is used as control replacement for executing FTFC.

The aircraft stability is analysed for icing and normal condition [9]. The simulated aircraft attributes were compared for normal flight and icing flight condition and observed that icing changes the geometry and thus equilibrium point of the aircraft. The controllability analysis of tandem quad-copter was carried out [10]. FDI scheme is developed by comparison of required attitude to the measured attitude [11]. Sensor fusion technique is applied to estimate fault in altitude estimation [12]. The real-time parameters of aerodynamic model were estimated using artificial intelligence [13]. The method of system identification was explained briefly for a small unmanned aircraft [14]. The real-time parameter estimation of aircraft was carried out using recursive least square and batch estimation method [15] and minimized error in each model. System identification using subscale methods were explained for small flexible aircraft [16]. FDI methods classified as data-driven or model reference approach for diagnosing fault[21]. So far, FTFC has been implemented in control reallocation with FDI or control by nullifying errors using proper corrective measures. The input signal or output performance was estimated for designing FDI.

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The fault may occur in actuator, measuring instrument. Sometimes, aircraft may undergo uncontrolled disturbance.

The aircraft performance may deviate from its expected value during malfunction in actuator, uncontrolled aircraft motion (environmental instability or structural failure). Most of the FDI and FTFC have limitation in classifying these fault sources and its effects. Implementation of FDI scheme is required for the effective application of FTFC without any inherent chaos in control logic [17].

Present study aims to develop MRFDI by combining the actuator feedback with aircraft parameter to identify accurate fault source. The aircraft mathematical model is simulated to get aircraft parameters and actuator feedback. Variances in aircraft parameter and actuator feedback is estimated from reference model to identify fault source by correlating among them. FTFC is developed by dual actuator for allocating primary actuator control to secondary actuator during the malfunction at primary actuator. The MRFDI diagnosis fault and gives protocol to FTFC for allocating control to primary and secondary actuator during malfunction.

II. AIRCRAFT PARAMETER ESTIMATION BY LS METHOD

A longitudinal linearized aircraft mathematical model is given in equation (1) and (2) [18].

$$\dot{x} = Ax + Bu \tag{1}$$

$$y = Cx + Du \tag{2}$$

where, $\dot{x} = [\dot{v}_x \dot{v}_z \dot{q} \dot{\theta}]^T$, $x = [v_x v_z q \theta]^T$ and $u = [\delta_e \delta_t]^T$. x, $\dot{x}$ are the velocity, acceleration response of the aircraft, u is the control input, u is the control input, A and B are the stability and control derivatives, C and D are the output matrices. A is the unknown parameter of the aircraft. v_x, v_z, q, θ of x are velocity in direction x, direction z, pitch rate and pitch angle. δ_e, δ_t of u are the elevator and throttle control input An aircraft hold autopilot system shown in Figure 1 [19]. is developed by applying baseline parameters values in equations (1) and (2) using flight parameter data given in Table 1. Aircraft mathematical model is simulated and aircraft responses are obtained as shown in Figure 2. Velocity (vx), the angle of attack (alph) and pitch angle (the) are shown in Figure 2(a). The reference altitude and aircraft altitude is shown in Figure 2(b). Input commands of an elevator (dele) and throttle (dthr) are shown in Figure 2(c).

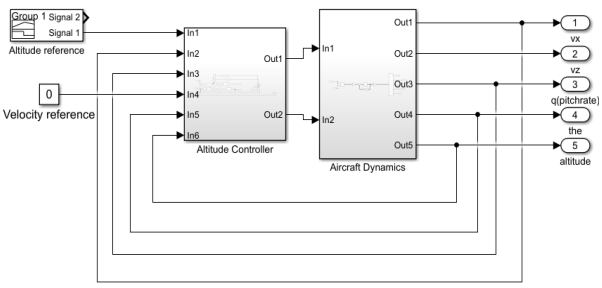

Figure 1. Altitude Hold Autopilot for system identification of a typical aircraft

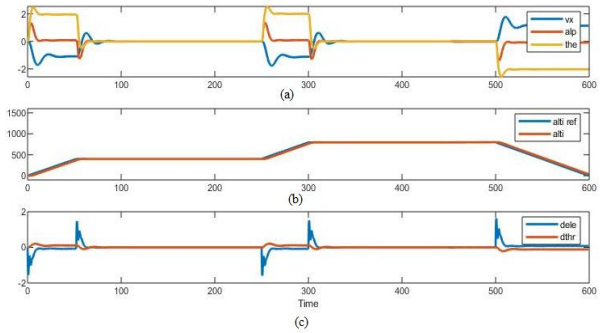

Figure 2. Flight path of altitude hold system

Different system identification methods namely output error, equation error and delta method is well established [20]. One of the simplest and reliable approaches is the least square method (LS) [16]. The simulated aircraft data is applied in equations (3), (4) and (5). The inputs X are $\dot{x} = [\dot{v}_x \dot{v}_z \dot{q} \dot{\theta}]^T$ and outputs of Y are $x = [v_x v_z q \theta]^T$. The unknown parameters are θ which is A and B of Equation (1). J in equation 4 is the cost function and minimization of it will result in equation (5).

$$Y = \theta X \tag{3}$$

$$J = ½ (Y - \theta X)^T (Y - \theta X) \tag{4}$$

$$\theta = (YX^T)(X^T X)^{-1} \tag{5}$$

The values of B747 base line parameters (base) and simulated parameters (LS) are given in Table 1 and found similar[22].

Table 1: Comparison of baseline parameter with estimated (LS) parameters.

Element A_{1j}	Baseline value	-0.00687	0.01394	0.00000	-9.81000
	LS method	-0.00687	0.01394	0.00000	-9.81000
Element A_{2j}	Baseline value	-0.09050	-0.31491	235.89279	0.00000
	LS method	-0.09050	-0.31491	235.89279	0.00000
Element A_{3j}	Baseline value	0.00039	-0.00336	-0.42817	0.00000
	LS method	0.00039	-0.00336	-0.42817	0.00000
Element A_{4j}	Baseline value	0.00000	0.00000	1.00000	0.00000
	LS method	0.00000	0.00000	1.00000	0.00000

The sequential least square (SLS) parameter estimation is given in equation (6) where N denotes the Nth second of experiment data [15]. The $\dot{x}, x$ of aircraft data is applied in Equation (7) and (8) to generate real time flight data. Then real time aircraft data is applied in Equation (6) to get real time parameter as shown in Figure 3. The results of SLS method is compared with LS method as given in Table 2.

$$\theta_{N+1} = (Y_{N+1} X_{N+!}^{\ T})(X_{N+1}^{\ T} X_{N+1})^{-1} \tag{6}$$

$$X_{N+1} = [x_N \quad x_{N+1}] \tag{7}$$

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$$Y_{N+1} = [y_N \quad y_{N+1}] \tag{8}$$

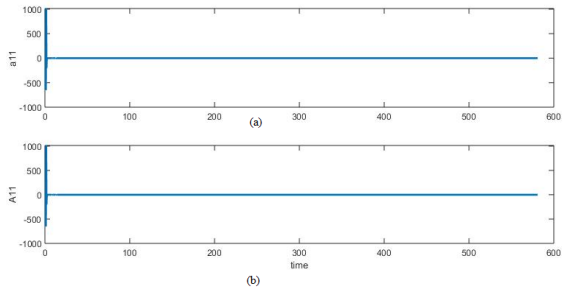

Figure 3. Convergence of parameters (SLS)

Table 2: Comparison of SLS, LS and baseline values of parameter

Base line value of A_{11}	LS value of A_{11}	SLS value of A_{11} (before 3sec)	SLS value of A_{11} (after 3s, A_{11})
-0.00687	-0.00687	0.23428	-0.00687

III. CONSTRUCTION OF MRFDI FAULT DIAGNOSIS METHOD

MRFDI is developed by cloning the autopilot model as shown in Figure 4. The actual model is assumed to be a real aircraft and the reference model to be a mathematical model of real aircraft. The fault is simulated by injecting steady state error in elevator as shown in Figure 5 during 350 sec. The aircraft experiencing change in altitude from reference aircraft as shown in Figure 6.

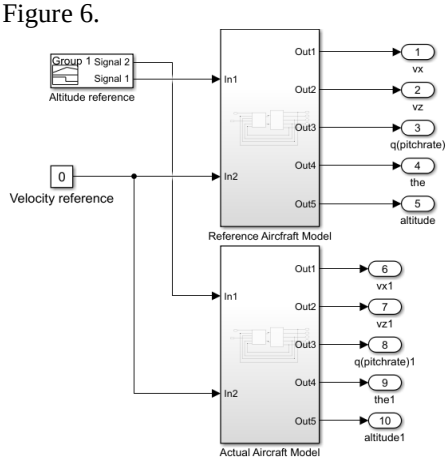

Figure 4. Actual aircraft and reference aircraft for model reference system

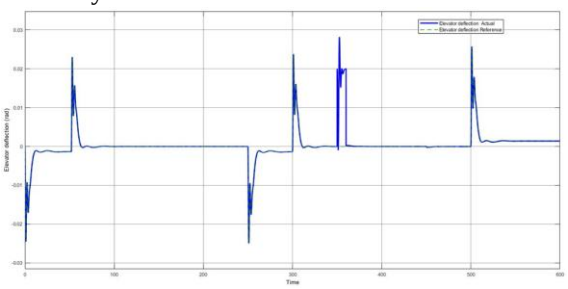

Figure 5. Fault injection and deviation of elevator from reference value – actuator feedback

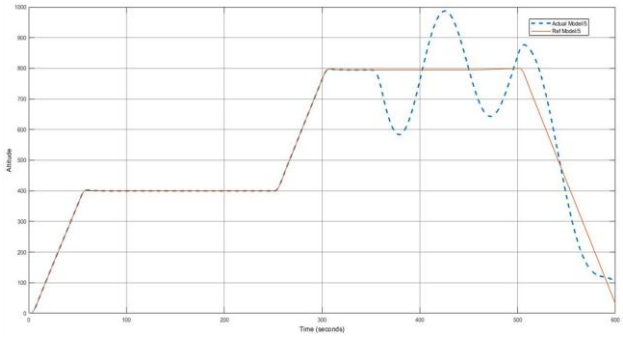

Figure 6. Aircraft altitude variation between reference and actual model due to fault injection at actuator

The MRFDI compares actuator feedback and aircraft parameters between reference model and actual model using logic given in Table 3.

Table 3. Fault diagnosis logic

Variance in Actuator Feedback	**Variance in aircraft parameter**	**Actuator fault**	**Instrument fault**	**Uncontrolled Disturbance**
1	0	0	1	0
1	1	1	0	0
0	1	0	0	1
0	0	0	0	0

The MRFDI uses fault diagnosis scheme shown in Figure 7. The MRFDI estimating variances in actuator feedback and parameter from model reference model and SLS method. The variance in actuator feedback shown in figure 5 and estimation of parameter variance is shown in figure 10. These variances are logically analysed as given in Table 3 and providing fault as flag value 0 and 1 as shown in Figure 7.

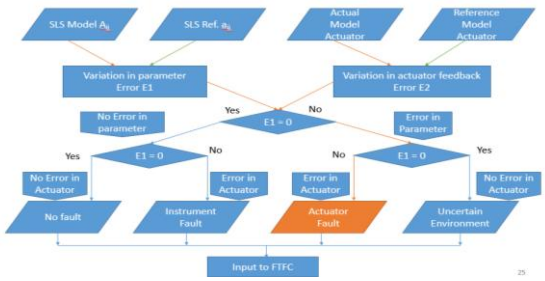

Figure 7. Fault diagnosis scheme for MRFDI

MRFDI diagnose fault by correlating variance in feedback of actuator and variance of aircraft parameter. A fault in actuator alters aircraft dynamics and thus aircraft parameter also changes. So actuator fault can identified by observing variance in actuator feedback and aircraft parameter. A fault in feedback instrument measures wrong value and does not changes aircraft dynamics. So, instrument fault can diagnose by observing variation only from actuator feedback. An uncontrolled aircraft motion changes aircraft dynamics alone. So, uncontrolled aircraft motion can observed by finding variance in aircraft parameter alone.

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Similar to elevator fault injection, fault is injected at feedback instrument and aircraft output to observe MRFDI fault diagnosis.

IV. DEVELOPMENT OF FTFC BY EMBEDING MRFDI

The FTFC is developed by adding twin actuator as shown in Figure 8.

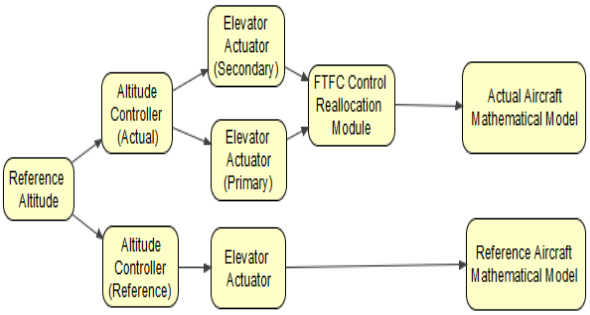

Figure 8. FTFC construction by twin actuator

Table 3. Fault Tolerant Flight Control – Control allocation logic

Variance in Actuator Feedback	Variance in aircraft parameter	Actuator fault	Instrument fault	Uncontrolled Disturbance	Control Allocation to Primary	Control Allocation to Secondary Actuator
1	0	0	1	0	1	0
1	1	1	0	0	0	1
0	1	0	0	1	1	0
0	0	0	0	0	1	0

The logic for FTFC function is given in Table 4 and implementation of MRFDI in FTFC is shown in Figure 9. The FTFC receives fault flag information from MRFDI as given in Table 3 by correlating variances in aircraft actuator and aircraft parameter. FTFC decides control allocation between primary and secondary actuator as given in Table 4. A fault in actuator induces variations in actuator feedback as well as aircraft parameters. So, the MRFDI sends protocol to FTFC as flag value 1 for actuator fault. Then FTFC allocates control to secondary actuator instead of primary actuator. A fault in actuator feedback instrument alters only feedback value. So, FTFC retains control in primary actuator. An uncontrolled aircraft motion alters aircraft dynamics alone. So, FTFC retains control to primary actuator.

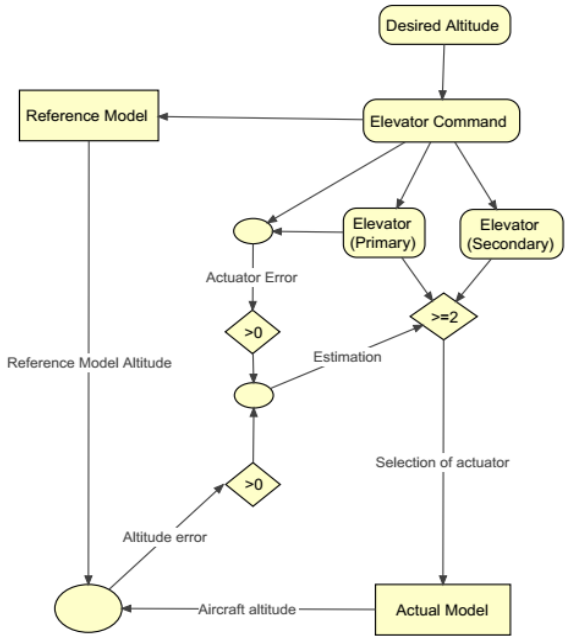

Figure 9. Implementation of MRFDI to FTFC

V. RESULTS AND DISCUSSION

The fault diagnosis of MRFDI for actuator fault is shown in Figure 11. The MRFDI estimates variances in aircraft parameters as shown in Figure 10. A fault is injected at elevator actuator during 350 sec and parameters of actual and reference model is observed in Figure 10 (a) and (b). The variances in parameters is observed in Figure 10 (c) which confirms the variation in aircraft altitude deviation from its reference value.

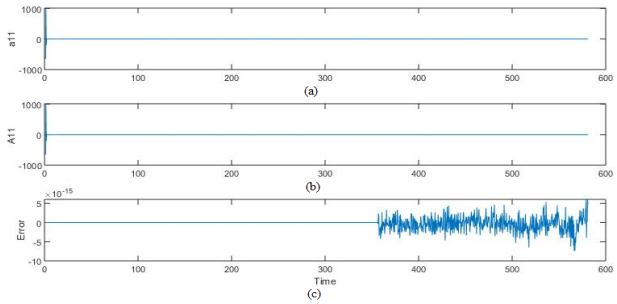

Figure 10. Estimation of variance in aircraft parameter

MRFDI estimates flag value as given in Table 3 which is shown in Figure 11. The variance in parameter is shown in Figure 11 (a) and actuator fault flag is shown in Figure 11 (b). The fault injection time and variance estimation time matches 350 sec. Since variances are observed from both actuator feedback as well as aircraft parameters, MRFDI estimates fault flag as 0 for instrument flag and environment error flag (uncontrolled aircraft motion). So finally, MRFDI diagnose actuator fault as fault flag 1 for actuator.

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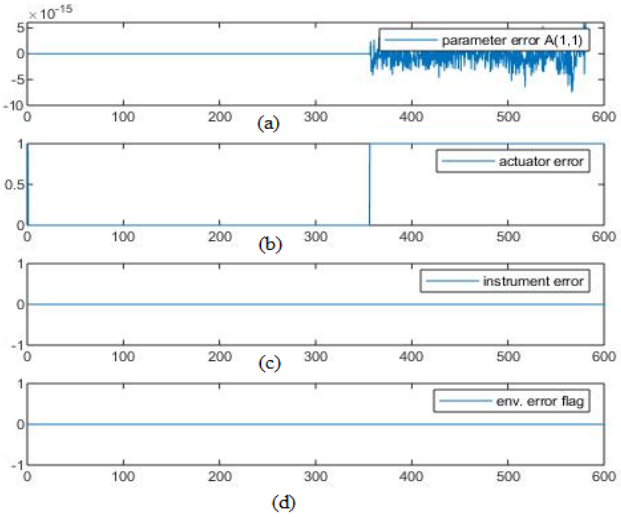

Figure 11. MRFDI fault diagnosis for actuator fault

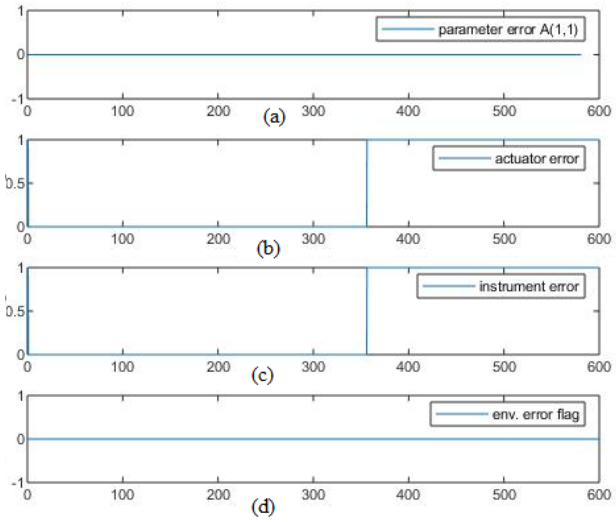

Figure 12. MRFDI fault diagnosis for actuator feedback instrument fault

Similarly, fault is injected to actuator feedback instrument and variances of aircraft parameters and actuator feedback was observed. The variation of aircraft parameter is shown in Figure 12(a). A fault in feedback instrument initially estimates fault flag value 1 for actuator as shown in Figure 12 (b). Then, as given in logic Table 3, MRFDI correlates both and estimating fault flag value 1 for instrument fault as shown in Figure 12 (c) and environment error as flag value 0 as shown in Figure 12 (c).

The uncontrolled aircraft motion is simulated as wind gust by adding fault in aircraft velocity. The change in parameters were observed as shown in figure 13 (a). Since aircraft actuator have working good as shown in Figure 13 (b), MRFDI estimates fault in environmental error as shown in Figure 13 (d).

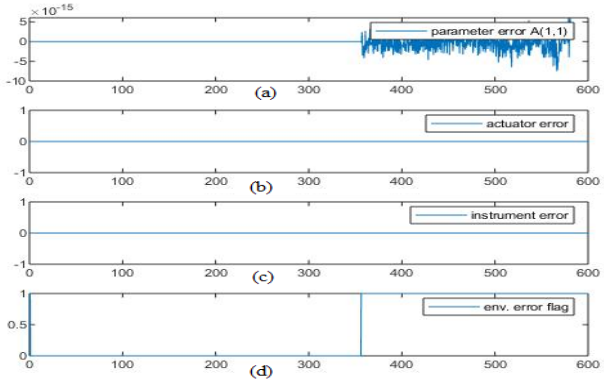

Figure 13. MRFDI fault diagnosis for uncontrolled aircraft motion

FTFC for actuator fault case develops control allocation signal to secondary actuator as shown in Figure 14. It is observed that FTFC allocating control to secondary actuator during malfunction primary actuator as given in Table 4. FTFC recovers aircraft altitude as shown in Figure 15.

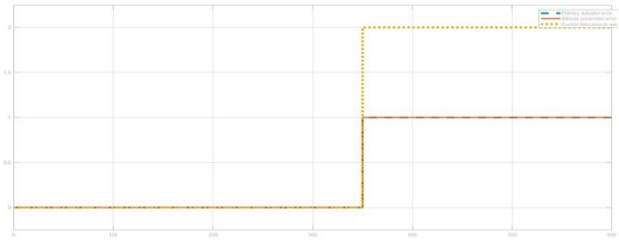

Figure 14. Control reallocation to secondary actuator during malfunction in primary actuator

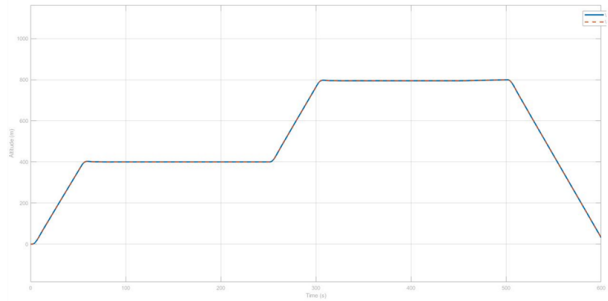

Figure 15. FTFC function during primary actuator fault – recovery of aircraft altitude

Similarly, FTFC is retaining control in primary actuator for instrument fault and environment fault as shown in Figure 16 and 17.

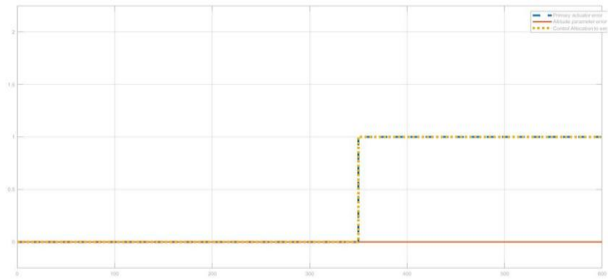

Figure 15. FTFC function during primary actuator fault – retention of primary actuator during instrument fault

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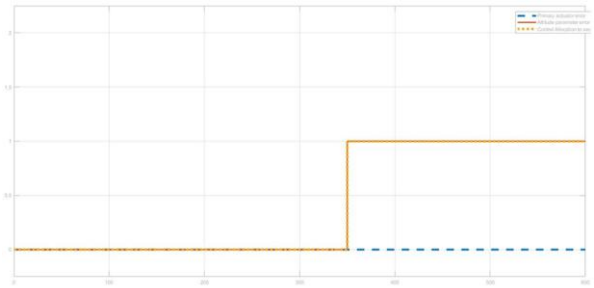

Figure 16. FTFC function during primary actuator fault – retention of primary actuator during uncontrolled aircraft motion

VI. CONCLUSION

MRFDI is tested for fault diagnosis of actuator fault, instrument error and environmental uncertainty. Results reveals that MRFDI is correlating variances in actuator feedback and aircraft parameter for robust fault diagnosis. FTFC is developed by incorporating twin actuator configuration and embedded with MRFDI. MRFDI injects protocol to FTFC to allocate control among primary and secondary actuator. FTFC is successfully allocating control to secondary actuator during occurrence of fault in actuator. The proposed fault diagnosis methodology demonstrates the ability to classify different fault sources existed in the aircraft. The future work is to implement system identification to prototype aircraft and test functionality of MRFDI and FTFC.

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