Fault Management of Guidance and Control System for Aerospace Vehicles

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ABSTRACT

Aerospace vehicles generally are safety-critical systems and they rely on sophisticated control systems. For an aerospace system to be fully reliable and highly safe, it requires to have the features of fault detection and diagnosis. In case of malfunction of the control actuators or sensors or other components, a conventional feedback control design may not meet the system requirement and may cause catastrophic failure. It therefore becomes a necessity to design fault tolerating control system design to improve the reliability of the system and maintain the overall system stability. The fault tolerance is achieved by fault detection and diagnosis and isolation of the fault. After the fault is recognized, the reconfiguration is carried out by means of redundancy on-board and the flight operation is continued. This paper gives the design of highly reliable flight control systems by employing fault detection and reconfiguration on-board by hardware and analytical redundancy techniques.

Keywords: *Fault Management, Flight Control System, Redundancy Management*

1. INTRODUCTION

An aerospace system consists of the on-board systems which have embedded systems for high computation, data processing, decision making and on-board command generation based on the physical environmental conditions. However, it is critical for the on-board systems to be highly reliable systems even in case of the harsh environmental conditions and with the real-time constraints. The impact of any fault in a component of a sub-system would lead to either degradation in the actual performance or overall system failure. In most of the failures, after the post flight analysis it comes out clear that though the fault in the system/ component could not be avoided but still would have been tolerated or mitigated by means of fault tolerant logics. The Fault tolerant mechanisms are designed to either reconfigure the system with the redundant sensor information or continue with the same sensor information but mitigate and have a graceful degradation in performance that may not cause heavy economical and human loss. This in turn increases the safety and reliability aspects of any aerospace system.

Design of a Fault Tolerant Flight Control System involves Detection of the Fault & Isolation from the main control loop with reconfigurable Control law, Design of Redundancy scheme to ensure non- degraded performance even under failure and to increase the overall reliability of the system.

2. LITERATURE REVIEW

FAULT ASSESSMENT& RISK IDENTIFICATION

Fault assessment refers to the systematic approach to evaluate the fault in a complex engineered system. The risk associated with each fault can be characterized by the Magnitude

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of the consequence that the fault can cause and Probability with which the fault may occur in the system causing adverse consequences. The Low Matrix index[10] is given to the unlikely faults and high index to the most frequent faults in a system. A fault that is frequent in nature and is critical and catastrophic becomes the highest risk for the system. This matrix index defines the area of concern in a system and aids in the decision to go ahead with either redundancy or fault tolerant mechanisms.

FLIGHT CONTROL SYSTEM

Failure of Flight Control system [3] can occur due to fault in either in components, structure, sensors or control actuation system. These faults change the control system dynamic behavior and cause instability thereby leading to structural damage. Sensor faults or incorrect reading would lead to incorrect decision on-board and failure of the system. In addition, when the failure of the sensor is catastrophic, it is always recommended to use redundant sensors and the sensor values can be taken based on the voting logics. However, with the increase in the number of sensors the cost of the system also increases. So, it is advised to analyze the trade-off between the cost and reliability and its effect of the sensor on the system and decide. Faults in actuation system would be categorized as either saturated value or struck at a random value. Either of the fault would lead to the loss of control action, as the actuator would not respond to the input given to it. Redundancy in actuation systems to achieve fault tolerance is often not preferred due to their high prices and large size and mass.

FAULT TOLERANT FLIGHT CONTROL

Fault Tolerant Control (FTC) [1] strategies can be categorized as passive and active approaches. In case of passive approach, Control law is designed to cater for stability in case of fault as well as fault free condition. For the control law to handle both the situations with or without degradation, it has to be very robust. In case of active approach, the fault detection and diagnosis information are required for the control reconfiguration. After the control is reconfigured, on-board decision-making would resume the mission activities without any intervention from the ground. Fault Tolerant Flight Control (FTFC) can be achieved by Fault Detection and Isolation (FDI) scheme followed by Re-configuration of control.

FDI Techniques are helpful to recognize the fault early in the system before it causes irreversible damage to the system. FDI Techniques [8] are generally categorized as Model-based approaches and Data-driven approaches. Model based FDI approaches are widely used and are more economical. Examples of Model based approaches are Kalman based approach, Parity-space approach or Observer-based approach. In these schemes, state estimation techniques are used that have mathematical models of the plants that are based on linear system theory. So, the techniques mostly depend on the accuracy and precision with which the system is modelled. Data driven based FDI approaches use Fuzzy logic, Artificial Neural Network (ANN) and Genetic Algorithm (GA) based approaches for detection of the fault in the system. These approaches provide more reliable results than the model-based approach.

Reconfiguration of the control law[9] is the important aspect of the fault tolerant control where the fault diagnosis is used to restructure the control loop and adapt the controller to the faulty system. Several techniques of Control structure modification, Real-time redesign or real-time search and optimization techniques of control loop and gain scheduling can be used for fault treatment.

3. Problem Definition

The aim of the project is to make the aerospace system more reliable. A way to offer increased reliability and safety is by means of a fault-tolerant flight control (FTFC) system design by means of redundancy physically or analytically and reconfiguration of autopilot design as shown in Figure 1.

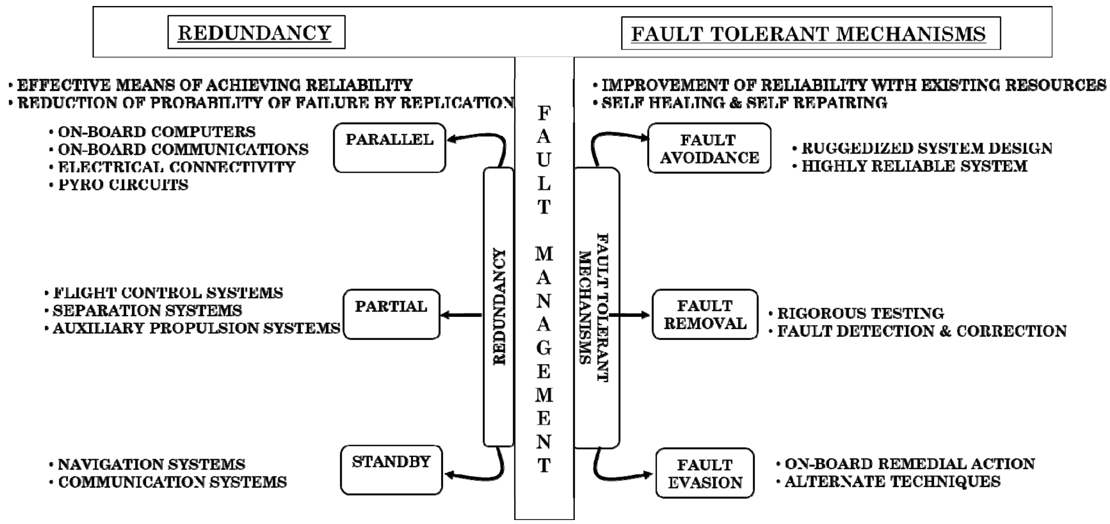

Figure 1: Fault Management

4. Implementation Methodology

The fault tolerance is achieved by detection and isolation followed by the reconfiguration. The implementation of the fault tolerance is as follows.

(i) Identification of fault in the actuation / sensor output based on the observer inputs.
(ii) Isolation of the fault from the control loop.
(iii) Switchover to redundant navigation sensor.
(iv) Reconfigure control law to take corrective measures.

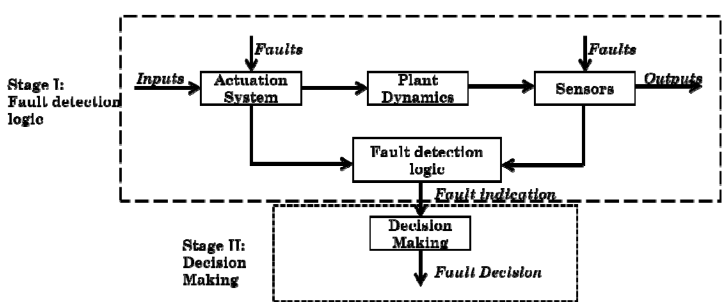

Figure 2: Fault Detection and Isolation

Stage I: Algorithm contains logic to check the values from actuator and sensor and decide fault based on the fault detection logic.

Stage-II: Decision rule is applied based on the fault detected and the control law is modified accordingly.

SENSOR FAULT TOLERANCE

Failures in navigation sensor may be due to sensor failure, processor failure, electronics failure, and communication bus failure or processor hang conditions. If there is any anomaly in the values of sensor data for consecutive 10 samples, then the corresponding sensor is isolated and the data is obtained from the corresponding redundant sensor.

Table 1: Sensor Fault Identification & Mitigation

	Failure Nodes		Action at Main Board	Action at Standby Board	Implications
1	RLG-Sensor Package	Ax, Ay, Az, Gx, Gy, Gz	Single Sensor Failure : Corresponding MEMS Sensor Data to be considered More than one Sensor Failure: Switch-over to MEMS	Single Sensor Failure : Corresponding MEMS Sensor Data to be considered More than one Sensor Failure: Switch-over to MEMS	Navigation with MEMS Sensor Package
2	MEMs-Sensor Package	Ax, Ay, Az, Gx, Gy, Gz	No Action	No Action	Navigation with RLG Sensor package only
3	GPS RX with Main Board		No Action	No Action	Navigation with RLG Sensor Package without GPS
4	GPS RX with Standby Board		No Action	No Action	Nil

ACTUATOR FAULT TOLERANCE

The system considered is a Flex Nozzle Control (FNC) system for a Solid Rocket Motor Propelled Aerospace vehicle. This FNC provides control in Pitch & Yaw plane by vectoring the main thrust from the rocket motor. FNC has two sensors called Main Sensor in the Actuator and Mirror sensor diametrically opposite to that of the main sensor.

The reason for having two sensors is to differentiate the common mode deflection, which may be caused due to the change in the internal chamber pressure and the actual deflection due to the control commands from autopilot.

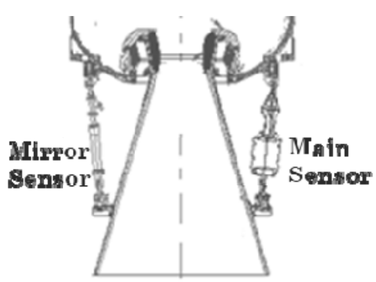

Figure 3: Typical Flex Nozzle Control System

In an ideal condition, the Main and Mirror sensor are expected to give similar deflection outputs. The differential mode signal will be given as controller feedback. The common mode and the differential mode signals can be calculated as per the equations below.

ISBN - 978-93-95038-50-8

$$Cmd_C = \frac{FB_{Main} + FB_{Mirror}}{2} \quad \text{……………. Equation 1}$$

$$Cmd_D = \frac{FB_{Main} - FB_{Mirror}}{2} \quad \text{……………. Equation 2}$$

One of the common modes of Failure is that of the malfunction of the mirror image sensors. Fault identification logic is designed to identify the malfunction of LVDT Sensors and to isolate from the controller feedback loop. Once the malfunction is identified, then the particular sensor is isolated from the controller feedback loop. However, for proper functioning of controller, at least one sensor is required. However, this sensor cannot handle the differentiation between common mode and differential mode signals. Therefore, an additional input such as Rocket Motor Chamber pressure (P_c), which is monitored is considered for autopilot gain scheduling.

RECONFIGURABLE AUTOPILOT

An autopilot is a closed loop system inside the main guidance subsystem that ensures that the vehicle achieves accelerations as commanded and maintains stability. Autopilot employs gain-scheduling techniques due to variation of velocity and altitude and the thrust, thereby scheduling the gains as a function of Mach number or Dynamic Pressure. The vehicle attitude information is obtained from the Inertial navigation system. Attitude errors are computed by knowing the desired attitude and sensed vehicle attitude and the error is fed to the control actuators. The Control system stabilizes the vehicle and executes the guidance commands to maneuver the vehicle in the desired trajectory. This is the most classical technique used in flight control system.

In reconfiguration based on the prior designed failure modes, the control filter changes are stored in the flight control system memory and when the fault is detected, the control filters are modified. With the recent trend of digital flight control systems, along with the gain scheduling modifications, control filter coefficients and time constants are modified.

5. RESULTS AND DISCUSSIONS

Being Time critical events, the objective of the testing is to see whether the failure is handled and the stand-by system takes over within the time frame to execute the next event.

SENSOR FAULT TOLERANCE

All Single node failure scenarios are designed based on Redundancy Management Scheme.

Failure scenarios include Data validity not OK, Data freezing and Bus Failure/Silence.

Test Methodology

The testing of the redundancy logics is carried out using the Zync SoC board, which consists of a Dual core processor making it suitable for the implementation of redundant navigation configuration. The requirements of the system are mapped to the implementation, a traceability matrix is prepared to introduce failures in the system, and the failures are introduced at critical time events.

Table 2: Requirement Traceability Matrix

Requirement ID	Test Condition	Test Case ID
1	Single Sensor Failure of RNAV-IMU (any one sensor failure among Ax, Ay, Az, Gx, Gy, Gz)	Test Case 1
2	More than one Sensor Failure of RNAV-IMU (Any one sensor failure among Ax, Ay, Az, Gx, Gy, Gz)	Test Case 2
3	Single /Multiple Sensor Failure of MEMS-IMU (Any one sensor failure among Ax, Ay, Az, Gx, Gy, Gz)	Test Case 3
4	GPS+GLONASS RX link failure with Main Board	Test Case 4
5	GPS+GLONASS RX link failure with Standby Board	Test Case 5

TEST RESULTS

Based on the traceability matrix the result of the test case with single sensor failure is presented below as shown in Table 3.

Table 3: Test Case-1 Results & Analysis

<table>
<tr><th colspan="5">Requirement Details</th></tr>
<tr><th>Requirement ID</th><th>Failure Node</th><th>Action at OBC (M)</th><th>Action at OBC (S)</th><th>Mission Implication</th></tr>
<tr><td>1</td><td>Single Sensor Failure of RNAV-IMU</td><td>Corresponding MEMS sensor data to be considered for Navigation</td><td>Corresponding MEMS sensor data to be considered for Navigation</td><td>Navigation with one MEMs sensors and all other RNAV sensors</td></tr>
<tr><td colspan="5">Test Case Details</td></tr>
<tr><td>Test Case Id</td><td>Aim</td><td>Test condition at OBC (M)</td><td>Test condition at OBC (S)</td><td>Observed Result</td></tr>
<tr><td>TC-1</td><td>To verify the switchover condition when data validity for Sensor data is Not OK in both OBC (M) & OBC(S) at the same time.</td><td>Sensor data set as NOT OK</td><td>Sensor data set as NOT OK</td><td>OBC (M) continued to execute further events.</td></tr>
<tr><td colspan="5">Test Result Analysis & Remarks</td></tr>
<tr><td colspan="5">OBC (M) continued with the execution of further events. Data of failed RINS sensor will be replaced with the MINGS sensor data. Navigation with one MINGS sensor and other two with RINS sensor will not have much implication on positional accuracies provided GPS data is available</td></tr>
</table>

ACTUATOR FAULT TOLERANCE

PRE-FLIGHT ESTIMATIONS

In an ideal case, for a Control Command to flex nozzle control, feedback is available from both Main and mirror image sensors as shown in Figure 4.

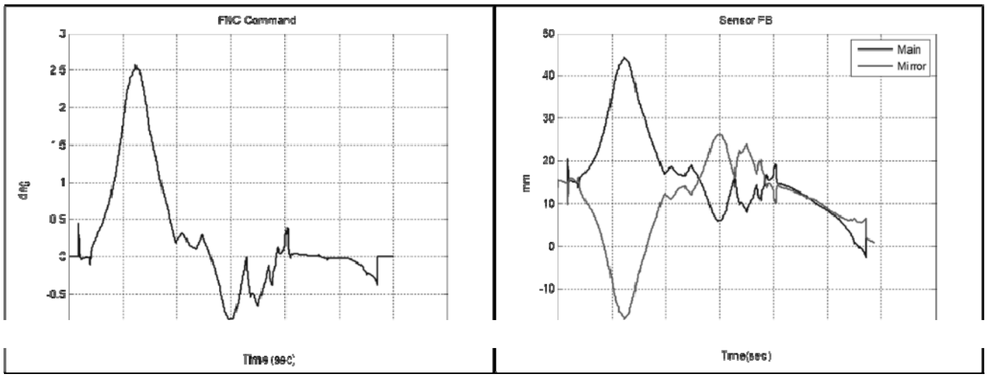

Figure 4: FNC Command & Feedback from Main and Mirror image sensors

The Actuator common mode signal is measured on ground for the system as a function of Chamber Pressure and the data is stored on-board. The Chamber Pressure data and the corresponding common mode deflection stored on-board are shown in Figure 5.

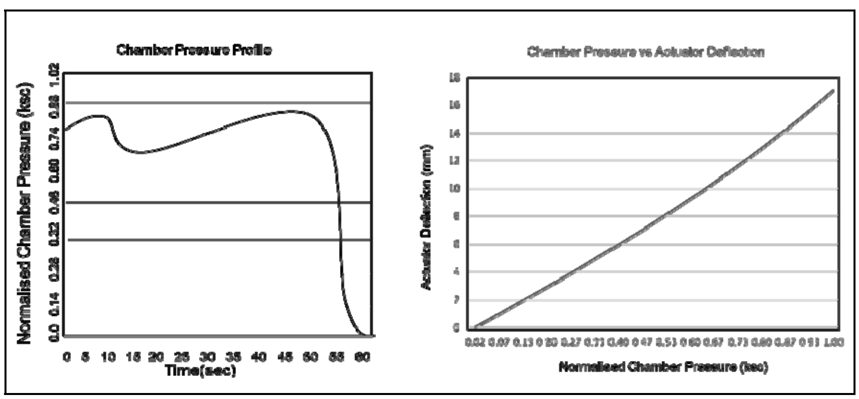

Figure 5: Chamber Pressure and Common Mode Actuator Deflection w.r.t Chamber Pressure

On-board fault identification and parameter estimation

The mirror image sensor (FB_{Mirror}) is declared faulty based on the fault check conditions and is isolated from the control loop. FB_{Mirror} can be declared faulty based on

$$\frac{d(FB_{Mirror})}{dt} \neq \frac{d(FB_{Main})}{dt} \quad \text{for 3 consecutive cycles}$$

In case of failure of the mirror image sensor, the FNC feedback value is available only from the main sensor and different output is obtained from the mirror sensor. The mirror image sensor output is calculated back from the stored Common mode signal and the Main sensor feedback signal.

$FB_{Mirror} = 2*Cmd_C - FB_{Main}$ ………… Equation 1

RECONFIGURATION OF AUTOPILOT

The reconfiguration of an autopilot is to be tested in a closed loop performance with the vehicle dynamics to understand and analyse the behavior of the system. The reconfiguration in autopilot is tested in the 6-DoF simulation test bed by means of injection of fault in the system and see the behavior of the autopilot whether the vehicle is controllable even in the fault condition.

TEST RESULTS

In case of a sensor failure, the sensor is declared faulty and isolated from the control loop. The Control autopilot is then reconfigured for the redundant sensor configuration and the vehicle is controlled back. The results of the 6-Dof simulation under fault condition are shown in Figure 6.

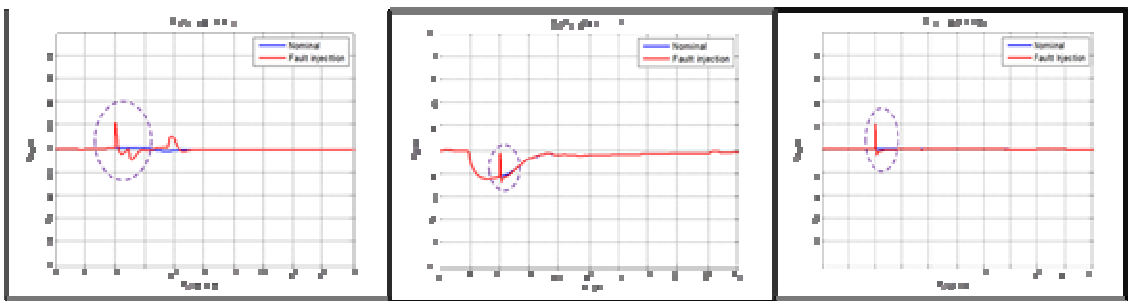

Figure 6: Comparison of Body Rates in faulty and fault free conditions

From the body rates it is evident that the autopilot is able to reconfigure the control gains in case of fault and the vehicle is controllable.

RELIABILITY ANALYSIS

In the design and development of the aerospace systems, due to the requirement of mission success even under the extreme unpredictable conditions, the reliability and safety[4] is to be considered as the top most priority. Monte-Carlo simulation method can be used to generate random numbers using mathematical models and link these numbers to the events. Monte-Carlo simulation is carried out with the 6-DoF simulation models and the failure of each system or sub-system failures are modelled in the system. Control failures would be modelled as Struck at faults. Struck at zero, struck at last command, struck at saturation are the various failure modes. The simulation is carried out with these failure modes at various instances of time and the performance of the system under all these conditions is evaluated.

SUMMARY & CONCLUSION

This Fault Management in Guidance and Control System for Aerospace vehicles can be achieved through fault identification, isolation and reconfiguration. Once the fault is identified in the system, the isolation of the sub-system from the main loop is necessary to prevent further damage to the system. And the fault mitigation is carried out by means of

ISBN - 978-93-95038-50-8

sub-system redundancy and further with the reconfiguration of the system. The fault management techniques have been developed for the multiple modes of failure in an aerospace vehicle and the performance of the system with implementation of this fault tolerant techniques have been studied under various conditions. The results have been presented and analyzed. The results show that these techniques can be effective in under faulty conditions. Few of these techniques have been tested in real time implementation and the computational loads incurred by the on-board computer. All these results have proved excellent performance of the system.

REFERENCES

1. BN Suresh, Failure Detection management in Launch Vehicle Avionics, Proceedings of IEEE International Conference on Industrial Technology 2000, 2000 pp.718-722 vol.2
2. D.R. Kiran, Chapter 26 - Failure Modes and Effects, Total Quality Management, Butterworth-Heinemann, 2017, Pages 373-389, ISBN 9780128110355, https://doi.org/10.1016/B978-0-12-811035-5.00026-X.
3. Verhaegen, M., Kanev, S., Hallouzi, R., Jones, C., Maciejowski, J., Smail, H. (2010). Fault Tolerant Flight Control - A Survey. In: Edwards, C., Lombaerts, T., Smaili, H. (eds) Fault Tolerant Flight Control. Lecture Notes in Control and Information Sciences, vol 399. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-11690-2_2
4. J H Wensley and D.D. Uhrich, Reliability and Cost Considerations for Launch Vehicle Avionics, 9th IEEE/AIAA/NASA Conference on Digital Avionics Systems, 1990, pp 117-124
5. Hyunsang park, Youdankim, Adaptive Fault Tolerant Flight Control for Input Redundant Systems Using a Nonlinear Reference Model, IEEE transactions on aerospace and electronic systems vol. 57, no. 5 October 2021
6. M.Thirumarimurugan, N.Bagyalakshmi, P.Paarkavi, Comparison Of Fault Detection And Isolation Methods: A Review, IEEE
7. C. Edwards et al. (Eds.): Fault Tolerant Flight Control, LNCIS 399, pp. 47–89
8. Ali Zolghadri , David Henry, J´erˆomeCieslak Denis Efimov, Philippe Goupil, Fault Diagnosis and Fault-Tolerant Control and Guidance for Aerospace Vehicles, From Theory to Application
9. Hajiyev Chingiz/ CaliskanFikret, Fault Diagnosis and Reconfiguration in Flight Control Systems
10. https://en.wikipedia.org/wiki/Risk_matrix