Fault Tolerant Servo Actuation System using MRAC for Launch Vehicle Electromechanical Actuator

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Abstract

Objective: This paper aims at designing a fault tolerant controller for a launch vehicle electro-mechanical actuator using model reference adaptive controller. Fault detection and diagnosis is a crucial topic in spacecraft operations and an important aspect of on board software with respect to safety, performance and reliability. Method/Statistical Analysis: This paper commences by the mathematical modeling of an electro-mechanical actuator based on a BLDC torque motor. The system is then subjected to a servo design and it is used as the model system for a model reference adaptive controller. MIT Rule is used as the control law for model based controller. The residuals for fault detection are generated by model reference adaptive control technique and it has the capability to detect and isolate the errors. The continuous operation of the system is obtained using a real time reconfiguration achieved using the model based approach. The entire system was simulated in MATLAB/SIMULINK software. Findings: The servo design of the launch vehicle electromechanical actuator system was developed using the mathematical model and the compensated system was used as the model system in the fault tolerant scheme using the model reference adaptive controller. The fault tolerant controller scheme was able to detect, isolate the faulty conditions and switch over the system output to the model output during the fault condition. The system is driven by the model output when fault occurs. The application of MIT rule is mainly for low frequency signals. Applications/Improvements: The system could be used in the launch vehicle applications, in order to make the system give ideal response during system failure. The control law used for the model reference adaptive controller can be improved and the Lyapnov method or theory of augmentation can be utilized instead of MIT Rule.

Keywords: Electro-Mechanical Actuator, Fault Tolerant Controller (FTC), Launch Vehicle, Model Reference Adaptive Controller (MRAC), MIT Rule

1. Introduction

A fault is defined as an undesired variation in one or more characteristic properties of a system variable from a nominal/acceptable behavior that leads to undesirable system performance, failure or glitch of the system. A fault/failure is a representation of the total interruption of the function, through a subsystem or the entire system. To make a system fault tolerant the primary goal is to detect the fault position and type. With the completion of fault diagnosis, a solution is to be developed which will bring the system back to its required performance conditions.

FTC is achieved by either hardware or analytical redundancy schemes. Figure 1 illustrates the hardware and analytical redundancy.

Redundancy supplied by a model is called analytical redundancy and there exists analytical redundancy in those cases where there are two or more different ways
to determine a variable $\theta$ by only using the observations $x(t)$, i.e. $\theta = f_1(x(t))$ and $\theta = f_2(x(t))$, and $f_1(x(t)) \neq f_2(x(t))$. Thus, analytical redundancy allows us to check if, $f_1(x(t)) = f_2(x(t))$.

Fault Detection, Isolation and Reconfiguration (FDIR) problem based on analytical redundancy is solved using a Model Reference Adaptive Control (MRAC). The model based problem can be divided into three steps. A set of variables called residuals are generated in the first step. In the next step a decision is taken on whether a fault has occurred. In addition to that the controller is reconfigured in response to any faults detected. Residual generation commences by developing a mathematical model of the launch vehicle actuator system.

## 2. System Description

A linear electromechanical actuator system based on a
Figure 3. Linear model of the EMA system.

Table 1. Nomenclature

| SYMBOL  | DESCRIPTION |
|---------|-------------|
| $B_e$   | Engine gimbal viscous damping coefficient |
| $B_m$   | Torque motor Viscous damping |
| $J_e$   | Moment of inertia of engine |
| $J_m$   | Moment of inertia of torque motor rotating assembly |
| $K_e$   | Back emf constant of torque motor |
| $K_{cf}$| Feedback gain of the current loop |
| $K_l$   | Equivalent stiffness of actuator mounting |
| $K_p$   | Scale factor for LVDT |
| $K_t$   | Torque sensitivity of motor (for $i_1 = 0$) |
| $l_m$   | Arm length of actuator lever |
| $n_b$   | Gear ratio of Ball screw |
| $N_{ch}$| Number of operating channels of torque motor |
A brushless DC motor is considered. The system block diagram and the linear model are as in Figure 2 and Figure 3.

The system nomenclature is as given in Table 1.

A DC source is used to power up the BLDC motor which is a closed loop position control. The compensated system is used as the reference model of MRAC system.

It specifies the ideal characteristic behavior of the adaptive control system. The EMA system is susceptible to the MRAC control scheme through the MIT rule as in Figure 4.

The Controller parameters are updated by using the equations.

Figure 4. Simulink model of MRAC with MIT rule.

Figure 5. Step response of the reference model in MRAS.
Where \( \theta_1 \) and \( \theta_2 \) are the controller parameters, \( u_C \) is the control variable and \( y \) is the output measured. The symbol \( \gamma \) represents the adaptation gain and its value is obtained on tuning as 0.008. The reference model step response in MRAS is as in Figure 5.

The MATLAB software is utilized in order to simulate the model which is as in Figure 6 and it can be seen that the model output is being tracked by the system output.

A feasible approach for real time automatic adjustment of the controllers is provided by the Model reference adaptive control. If a fault occurs in the output of the system, some type of configuration is added to the system in order to detect, isolate and reconfigure the system. Thus a model which manifests an exemplary performance of the plant under similar conditions is developed. The same reference input is given to both the system and the model.

### 3. Residual Generation for Detection of Fault

Generation of residual signals using available inputs and outputs from the monitored system is termed as residual generation. It indicates the occurrence of fault if any. Under normal working/no fault condition it is zero or close to zero. In the presence of fault it moves away from zero value. Thus it can be concluded that the residual is characteristically independent of process input and outputs, in ideal conditions. The procedure used to compute residual is called a residual generator as in Figure 7. Such a procedure is exploited in extract fault symptoms in an EMA system in a launch vehicle. In such a system the differences between the measured and estimated signals is represented by the residual generated. Thus fault can be detected.

\[
\frac{d\theta_1}{dt} = -\gamma \frac{a_m u_C}{\rho + a_m} e
\]  

\[
\frac{d\theta_2}{dt} = \gamma \frac{a_m y}{\rho + a_m} e
\]  

**Figure 2.** System output and model output with MIT rule obtained in Simulink.
4. Simulation Results

Model reference adaptive control provide a systematic technique for the automatic adjustment of controllers, in order to attain a desired level of control system performance even when the parameters of the plant dynamic model/mathematical model are unrevealed or change in time.

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**Figure 7.** Structure of residual generator.

**Figure 8.** FDIR scheme with MRAC.
Figure 9. Residual in the system.

Figure 10. Output of the reconfigurable system.
The comparison of the residuals with the threshold which is determined based on the characteristics of the normal state aids in detecting the fault. In Figure 8, scope 1 gives the residual. Fault detection is followed by fault isolation which will help in determining the type and location of faults. After a failure has been detected and isolated, then perform a control reconfiguration to preserve the desired performance in face of the failure occurrence. If a fault occurs in the system output, it switches to model output. Therefore model output will be driving the system.

From Figure 8 the fault occurs at 25 seconds. Residual is as in Figure 9. Even in absence of faults, the residuals need not be zero due to existence of noise in the system. The output of reconfigurable system is as in Figure 10, which is same as the model output.

5. Robustness to Plant Parameter Variations

The robustness of the model-based scheme can be assessed by varying the plant parameters that can introduce a fault in the system. The value of \( N_{ch} \) (Number of operating channels of torque motor) is changed from 4 to 2 for checking the robustness of the FDIR system. The change is first introduced in the conventional compensator design of the system and we can observe that the performance is not met as in Figure 11. It can be observed that the required bandwidth is not obtained with parameter variation.

The same change in parameter is made in the FDIR system developed using MRAC and it can be seen in Figure 12 that the value of residual is maintained below

![Bode Diagram](image-url)

**Figure 11.** Conventionally compensated system performance with parameter variation.
the threshold value and thus system remains robust to small parameter variations.

6. Conclusion

The mathematical model of an electromechanical actuation system used in launch vehicle application is considered. The compensated system is used as the reference model for the model reference adaptive control to develop a fault tolerant system. The FTC scheme was able to detect, isolate the faulty conditions and switch over the system output to the model output during the fault condition. The model output will be driving the system when the fault occurs. The simulation was done using MATLAB/SIMULINK software. Only low frequency signals are subjected to MIT rule of MRAC. Future work is to implement a new controller for high frequency signals.

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8. References

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