Design of an Adaptive Actuator Failure Compensation System for a Space Transportation System

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Abstract: This paper presents a new actuator failure compensation system for a space transportation system. The proposed system is designed to maintain the desired values of vehicle angular velocity if a partial actuator failure occurs by using model reference adaptive control (MRAC). If a failure occurs, this system is activated to generate the required “control effect” using redundant control deflections. Numerical simulation was performed to confirm the validity of the proposed system.

1. Introduction
Space transportation systems require some tolerance for failure. To this end, Ochi and Kanai designed the reconfigurable flight control system for failure compensation. Their system is designed to combine the feedback linearization method with an adaptive estimation mechanism in order to maintain flight performance without needing to determine the defective component [1], [2].

In this paper, we focus on an actuator failure compensation system for a space transportation system with actuator redundancies by using model reference adaptive control (MRAC). The proposed system is designed to generate the required “control effect” if the actuator fails. A numerical simulation was performed to confirm the validity of the proposed system.

2. Plant Dynamics
A linear approximation of the rotational motion of the vehicle is described by

\[
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix}
= 
\begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix}
+ 
\begin{bmatrix}
b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\
b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\
b_{31} & b_{32} & b_{33} & b_{34} & b_{35}
\end{bmatrix}
\begin{bmatrix}
\delta_a \\
\delta_a \\
\delta_a
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
\delta_e \\
\delta_e \\
\delta_e
\end{bmatrix}
+ 
\begin{bmatrix}
\delta_\alpha \\
\delta_\beta \\
\delta_\gamma
\end{bmatrix}
\tag{1}
\]

As shown in Figure 1, \(p, q, \) and \(r\) represent the angular velocity of the roll, pitch, and yaw, and \(\delta_{\alpha, L}, \delta_{\alpha, R}, \delta_{\beta, L}, \) and \(\delta_{\gamma}\) express the angles of the left/right aileron, left/right elevator, and rudder, respectively. Eq. (1) can be rewritten as

\[
\dot{x} = Ax + B\delta = Ax + f_m.
\tag{2}
\]

\[
f = [f_p, f_q, f_r]^T = B\delta_m.
\tag{3}
\]

where the constant coefficient matrices \(A \in \mathbb{R}^{3 \times 3}\) and \(B \in \mathbb{R}^{3 \times 1}\) are composed of the stability and control derivatives, respectively.

In this paper, it is assumed that the aircraft has redundancy of the ailerons and elevators by allowing right and left ailerons/elevators to be operated independently. The vector \(f = B\delta\) is treated as the “control effect”.

3. Failure Compensation System
In this section, an adaptive actuator failure compensation system is presented. The following vector \(f_m\) represents the desired control effect without actuator failure, which corresponds to the control effect vector \(f\) in Eq. (3).

\[
f_m = [f_{p_m}, f_{q_m}, f_{r_m}] = B\delta_m.
\tag{6}
\]

The purpose of the proposed system is to guarantee, if the actuator fails, that the control effect vector \(f\) corresponds to vector \(f_m\) by using the redundant control surfaces described by \(\delta\):

\[
f = f_m\tag{7}
\]

The reference model of the actuator dynamics is determined by Eq. (8). This model indicates the actuator dynamics without failure.

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\[
\begin{align*}
\delta_m &= A_m \delta_m + B_m u_m \\
\delta_m &= C \delta_m
\end{align*}
\]  
(8)

The vectors and matrices are \(A_m \in \mathbb{R}^{10 \times 10}\), \(B_m \in \mathbb{R}^{10 \times 5}\), \(\delta_m \in \mathbb{R}^{10 \times 1}\), and \(u_m \in \mathbb{R}^{5 \times 1}\). The following output equation corresponds to Eq. (5).

\[
\delta_m = C \delta_m = \delta_m + c \dot{\delta}_m
\]
(9)

The input for the reference model is determined to achieve the desired control deflection with the pseudo-inverse matrix \(B^+\).

\[
u_m = B^+ r_d = B^+ (BB^T)^{-1} r_d
\]
(10)

\(r_d \in \mathbb{R}^{5 \times 1}\) represents the angle vector of the aileron, elevator, and rudder to maintain the desired angular velocities, and \(B^+ \in \mathbb{R}^{10 \times 5}\) is the pseudo-inverse matrix. Here, the control law is designed such that the required deflection signal \(r_d\) is adaptively determined using the control surface actuators.

\[
u = K_d(t) \delta_d + K_c(t) r_d + v(t)
\]
(11)

Here, \(K_d(t)\), \(K_c(t)\), and \(v(t)\) indicate the control gains and the command signal. These values are generated by the following parameter adjustment laws, which are based on Lyapunov’s second law to guarantee the stability of the system.

\[
\begin{align*}
K_d(t) &= -B_{d0} C^T B^T P_0 e_f(t) \delta_f(t) dt + K_d(0) \\
K_c(t) &= -B_{b0} C^T B^T P_0 e_f(t) r_d(t) dt + K_c(0) \\
v(t) &= -B_{b0} C^T B^T P_0 e_f(t) dt + v(t)
\end{align*}
\]
(12-14)

The second term on the right-hand side of each equation is the initial value of the parameters, \(P\) is a weighting matrix, and \(B_{bd}\) is defined as follows:

\[
B_{bd} = BC B_d
\]
(15)

4. Numerical simulations

Numerical simulation was performed to verify the effectiveness of the proposed system. Table 1 shows the simulation conditions.

**Table 1. Simulation conditions**

<table>
<thead>
<tr>
<th>Command (r_d)</th>
<th>10 [deg] (step input)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure mode</td>
<td>Right elevator is fixed at (\delta_d = -30) [deg] at (t = 5) [s]</td>
</tr>
<tr>
<td>Model</td>
<td>Reference [3]</td>
</tr>
</tbody>
</table>

Figure 2 shows the time histories of the pitch, roll, and yaw rates of the vehicle. Figure 3 indicates the time histories of the control effects \(f\) and \(f_m\). In figures 2 and 3, the solid lines are the actual angular velocities \(\dot{x}\) and the control effect \(\dot{f}\), and the dotted lines represent the reference output \(\dot{x}_m\) and the vector \(\dot{f}_m\), respectively. According to these figures, the proposed system distributes the command signals to each actuator appropriately. The angular velocity of the vehicle \(\dot{x}\) and the control effect \(\dot{f}\) are converged to \(\dot{x}_m\) and \(\dot{f}_m\), despite the actuator failure (at \(t = 5\) [s]).

5. Conclusions

This paper presents a new actuator failure compensation system using model reference adaptive control (MRAC) for a space transportation system. The effectiveness of the proposed system is verified against a right elevator failure by numerical simulation.

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6. Reference

