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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

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & 0 \\ b_{31} & b_{32} & 0 & 0 & b_{35} \end{bmatrix} \begin{bmatrix} \delta_{aL} \\ \delta_{aR} \\ \delta_{eL} \\ \delta_{eR} \\ \delta_{r} \end{bmatrix} . \quad (1)$$

As shown in Figure 1, *p*, *q*, and *r* represent the angular velocity of the roll, pitch, and yaw, and δ_{aL}, δ_{aR}, δ_{eL}, δ_{eR}, and δ_r express the angles of the left/right aileron, left/right elevator, and rudder, respectively. Eq. (1) can be rewritten as

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{B\delta} = \boldsymbol{Ax} + \boldsymbol{f}\ , \quad (2)$$

$$\boldsymbol{f} = [\, f_P \quad f_Q \quad f_R \,]^T = \boldsymbol{B\delta}\, , \quad (3)$$

where the constant coefficient matrices $\boldsymbol{A} \in \boldsymbol{R}^{3\times3}$ and $\boldsymbol{B} \in \boldsymbol{R}^{5\times1}$ 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 $\boldsymbol{f} = \boldsymbol{B\delta}$ is treated as the “control effect”.

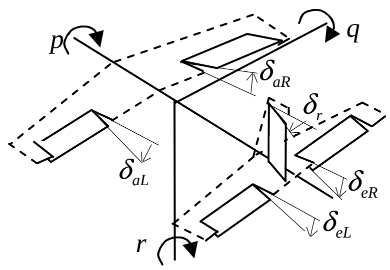

Figure 1. Definitions of positive and negative control deflections

Here, the actuator dynamics is treated as following five sets of the second-order systems:

$$\begin{cases} \dot{\boldsymbol{\delta}}_{\boldsymbol{a}} = \boldsymbol{A}_{\boldsymbol{\delta}}\boldsymbol{\delta}_{\boldsymbol{a}} + \boldsymbol{B}_{\boldsymbol{\delta}}\boldsymbol{u} + \boldsymbol{d}, \\ \boldsymbol{\delta} = \boldsymbol{C}\boldsymbol{\delta}_{\boldsymbol{a}}, \end{cases} \quad (4)$$

where $\boldsymbol{\delta}_{\boldsymbol{a}} \in \boldsymbol{R}^{10\times1}$ is the state vector composed of the deflection angles and its rates of change, $\boldsymbol{A}_{\boldsymbol{\delta}} \in \boldsymbol{R}^{10\times10}$ is the coefficient matrix of the state vector, the control input $\boldsymbol{u} \in \boldsymbol{R}^{5\times1}$ is the vector of the deflection commands for the each actuator, $\boldsymbol{B}_{\boldsymbol{\delta}} \in \boldsymbol{R}^{10\times5}$ is the coefficient vector of $\boldsymbol{u}$, $\boldsymbol{d} \in \boldsymbol{R}^{10\times1}$ is the vector of disturbances, and the output $\boldsymbol{\delta}$ is the vector of the angles of the control surface. In addition, the following output equation is also introduced to construct the adaptive control law in the next section. This output vector comprises the angles of the control surfaces and their respective rates of change.

$$\boldsymbol{\delta_1} = \boldsymbol{C_1}\boldsymbol{\delta_a} = \boldsymbol{\delta} + \alpha\dot{\boldsymbol{\delta}} \quad (5)$$

3. Failure Compensation System

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

$$\boldsymbol{f_m} = [\, f_{mP} \quad f_{mQ} \quad f_{mR} \,]^T = \boldsymbol{B\delta_m} \quad (6)$$

The purpose of the proposed system is to guarantee, if the actuator fails, that the control effect vector $\boldsymbol{f}$ corresponds to vector $\boldsymbol{f_m}$ by using the redundant control surfaces described by $\boldsymbol{\delta}$

$$\boldsymbol{f} = \boldsymbol{f_m} \quad (7)$$

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

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$$\begin{cases} \dot{\boldsymbol{\delta}}_{am} = \boldsymbol{A}_m \boldsymbol{\delta}_{am} + \boldsymbol{B}_m \boldsymbol{u}_m \\ \boldsymbol{\delta}_m = \boldsymbol{C} \boldsymbol{\delta}_{am} \end{cases} \tag{8}$$

The vectors and matrices are $\boldsymbol{A}_m \in \boldsymbol{R}^{10\times10}$, $\boldsymbol{B}_m \in \boldsymbol{R}^{10\times5}$, $\boldsymbol{\delta}_{am} \in \boldsymbol{R}^{10\times1}$, and $\boldsymbol{u}_m \in \boldsymbol{R}^{5\times1}$. The following output equation corresponds to Eq. (5).

$$\boldsymbol{\delta}_{1m} = \boldsymbol{C}_1 \boldsymbol{\delta}_{am} = \boldsymbol{\delta}_m + \alpha \dot{\boldsymbol{\delta}}_m \tag{9}$$

The input for the reference model is determined to achieve the desired control deflection with the pseudo-inverse matrix $\boldsymbol{B}^+$.

$$\boldsymbol{u}_m = \boldsymbol{B}^+ \boldsymbol{r}_d = \boldsymbol{B}^T \left(\boldsymbol{B}\boldsymbol{B}^T\right)^{-1} \boldsymbol{r}_d \tag{10}$$

$\boldsymbol{r}_d \in \boldsymbol{R}^{3\times1}$ represents the angle vector of the aileron, elevator, and rudder to maintain the desired angular velocities, and $\boldsymbol{B}^+ \in \boldsymbol{R}^{5\times3}$ is the pseudo-inverse matrix. Here, the control law is designed such that the required deflection signal $\boldsymbol{r}_d$ is adaptively determined using the control surface actuators.

$$\boldsymbol{u} = \boldsymbol{K}_\delta(t)\boldsymbol{\delta}_a + \boldsymbol{K}_r(t)\boldsymbol{r}_d + \boldsymbol{v}(t) \tag{11}$$

Here, $\boldsymbol{K}_\delta(t)$, $\boldsymbol{K}_r(t)$, and $\boldsymbol{v}(t)$ 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.

$$\boldsymbol{K}_\delta(t) = -\boldsymbol{B}_{b\delta}^T \boldsymbol{C}_1^T \boldsymbol{B}^T \boldsymbol{P} \int \boldsymbol{e}_f(t) \boldsymbol{\delta}^T(t) dt + \boldsymbol{K}_\delta(0) \tag{12}$$

$$\boldsymbol{K}_r(t) = -\boldsymbol{B}_{b\delta}^T \boldsymbol{C}_1^T \boldsymbol{B}^T \boldsymbol{P} \int \boldsymbol{e}_f(t) \boldsymbol{r}_d^T(t) dt + \boldsymbol{K}_r(0) \tag{13}$$

$$\boldsymbol{v}(t) = -\boldsymbol{B}_{b\delta}^T \boldsymbol{C}_1^T \boldsymbol{B}^T \boldsymbol{P} \int \boldsymbol{e}_f(t) dt + \boldsymbol{v}(0) \tag{14}$$

The second term on right-hand side of each equation is the initial value of the parameters, $\boldsymbol{P}$ is a weighting matrix, and $\boldsymbol{B}_{b\delta}$ is defined as follows:

$$\boldsymbol{B}_{b\delta} \equiv \boldsymbol{B}\boldsymbol{C}_1\boldsymbol{B}_\delta \tag{15}$$

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

Command $\boldsymbol{r}_d$	10 [deg] (step input)
Failure mode	Right elevator is fixed at δ_{eR} = -30 [deg] at t = 5 [s]
Model	Reference [3]

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 $\boldsymbol{f}$ and $\boldsymbol{f}_m$. In figures 2 and 3, the solid lines are the actual angular velocities $\boldsymbol{x}$ and the control effect $\boldsymbol{f}$, and the dotted lines represent the reference output $\boldsymbol{x}_m$ and the vector $\boldsymbol{f}_m$, respectively. According to these figures, the proposed system distributes the command signals to each actuator appropriately. The angular velocity of the vehicle $\boldsymbol{x}$ and the control effect $\boldsymbol{f}$ are converged to $\boldsymbol{x}_m$ and $\boldsymbol{f}_m$, despite the actuator failure (at t = 5 [s]).

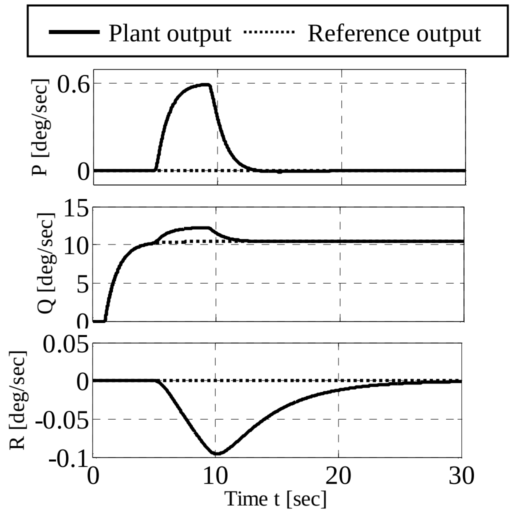

Figure 2. Time histories of angular rate

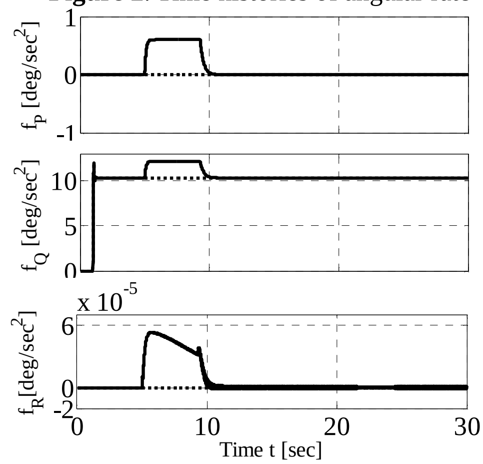

Figure 3. Time histories of control effect

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

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