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Comparing the Performance of Reference Trajectory Management and Controller Reconfiguration in Attitude Fault Tolerant Control

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Abstract. Reference trajectory management is a method to modify reference trajectories for the faulty system. The modified reference trajectories define new maneuvers for the system to retain its pre-fault dynamic performance. Controller reconfiguration is another method to handle faults in the system, for instance by adjusting the controller parameters (coefficients). Both of these two methods have been considered in the literature and are proven to be capable of handling various faults. However, the comparison of these two methods has not been considered sufficiently. In this paper, a controller reconfiguration mechanism and a reference trajectory management are proposed for the spacecraft attitude fault tolerant control problem. Then, these two methods are compared under the same conditions, and it is shown that the proposed controller reconfiguration has better performance than the proposed reference trajectory management. The reason is that the controller reconfiguration has more variables to modify the closed-loop system behavior.

1 Introduction

Fault occurrence in closed-loop system brings about one of the challenging situations in control problem. For severe faults, the conventional feedback controller may not show satisfactory performance [1]. Fault tolerant control (FTC) has been proposed as a method to handle faults in control systems. FTC is divided into two main parts: Active FTC (AFTC) and Passive FTC (PFTC). PFTC has a fixed structure and is designed to be robust against a pre-defined set of faults [1]. This approach has limited capabilities from a fault-tolerance point of view [1]. AFTC reconfigures the closed-loop system actively to recover the performance of the faulty system [1]. Essential components of this type of controller are fault detection and diagnosis (FDD), reconfigurable controller and a reconfiguration mechanism [1-3]. Almost an uncountable number of papers, books, and reports have considered AFTC. [4] and [5] are recently published review papers that have considered the FTC literature in aerospace and spacecraft attitude control problems.

One of the components of AFTC is the reference trajectory management (RTM) [1]. The main responsibility of RTM is to adjust/modify the reference trajectories to retain the pre-fault performance of the system [6]. There are several papers that have studied the effects of RTM on the performance and stability of the post-fault system [7-10]. According to these works, RTM has been able to deal with the actuator faults/failures efficiently.

According to the literature, AFTCs have been designed considering a variety of methods and disciplines. However, to the authors' best knowledge, no comparison is made between the performance of RTM and controller reconfiguration. This point is the subject of the present paper.

It is shown that under the same conditions, reconfiguring the controller (adjusting the controller parameters, in this paper) has a better performance than the RTM. The reason is that the proposed controller reconfiguration has more variables to modify the closed-loop system. This fact is verified via a simulation.

This paper consists of the following sections: Section 2 considers the spacecraft dynamics and control problem. The proposed controller reconfiguration and RTM are presented in section 3. Section 4 presents the numerical simulation and finally, the paper ends with a conclusion.

2 Dynamics and control

According to [11], if the components of $\mathbf{u}''$ are selected as:

$$u_1'' = \ddot{q}_{1,\mathrm{r}} - k_{\dot{q}_1}\left(\dot{q}_1 - \dot{q}_{1,\mathrm{r}}\right) - k_{q_1}\left(q_1 - q_{1,\mathrm{r}}\right) \tag{1}$$

$$u_2'' = \ddot{q}_{2,\mathrm{r}} - k_{\dot{q}_2}\left(\dot{q}_2 - \dot{q}_{2,\mathrm{r}}\right) - k_{q_2}\left(q_2 - q_{2,\mathrm{r}}\right) \tag{2}$$

$$u_3'' = \ddot{q}_{3,\mathrm{r}} - k_{\dot{q}_3}\left(\dot{q}_3 - \dot{q}_{3,\mathrm{r}}\right) - k_{q_3}\left(q_3 - q_{3,\mathrm{r}}\right) \tag{3}$$

the closed loop system of the spacecraft will be asymptotically stable, provided the first and second order derivatives of the reference quaternion vector ($\mathbf{q}_r$) exist and controller coefficients (k_{q_1}, k_{q_2}, k_{q_3}, $k_{\dot{q}_1}$, $k_{\dot{q}_2}$, $k_{\dot{q}_3}$) are positive.

3 Controller reconfiguration and RTM

Depending on the method used (controller reconfiguration or RTM), the following cases will be considered:

3.1 Controller reconfiguration

In this case, the closed-loop system structure is shown in Fig. 1:

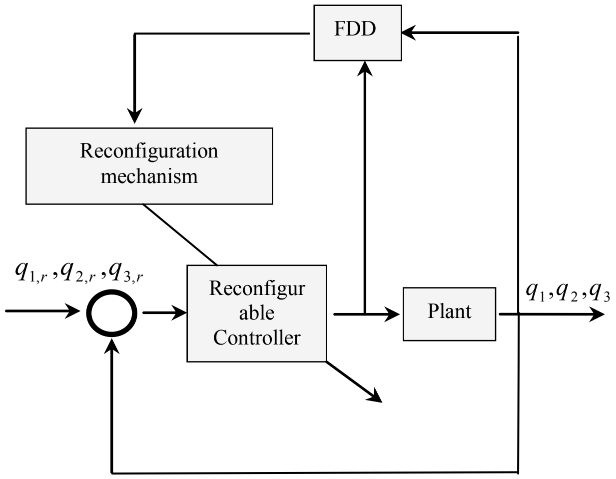

Figure 1. Closed-loop structure (controller reconfiguration).

The controller parameters are adjusted to compensate for the effect of faults. Block diagram of the reconfiguration mechanism is illustrated in Fig. 2.

The controller coefficients are determined at fixed Δt intervals. Then, a cubic spline [12] passes through these points to make the controller coefficients smooth functions of time. The simulation loop is repeated several times until the stopping criterion is satisfied. The subscript *sim* is used to confirm the simulation. The output of Fig. 2 is the smooth curves (controller coefficients) produced by cubic splines.

3.2 Reference trajectory management

In this case, the closed-loop system structure is shown in Fig. 3.

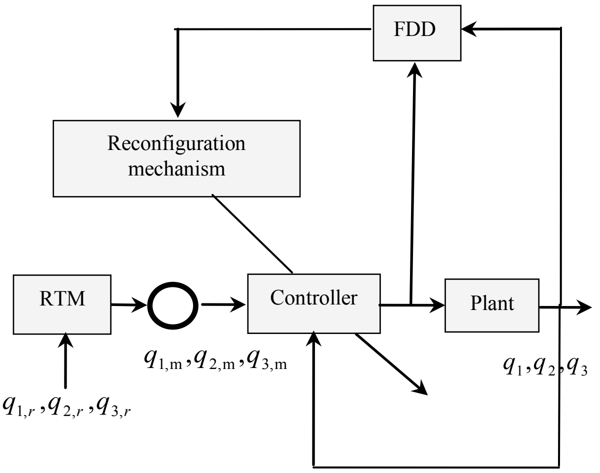

Figure 3. Closed-loop structure (RTM).

It should be noted that in this case, Eqs. 1, 2 and 3 are changed to the following form:

$$u_1'' = \ddot{q}_{1,\mathrm{m}} - k_{\dot{q}_1}\left(\dot{q}_1 - \dot{q}_{1,\mathrm{m}}\right) - k_{q_1}\left(q_1 - q_{1,\mathrm{m}}\right) \quad (4)$$

$$u_2'' = \ddot{q}_{2,\mathrm{m}} - k_{\dot{q}_2}\left(\dot{q}_2 - \dot{q}_{2,\mathrm{m}}\right) - k_{q_2}\left(q_2 - q_{2,\mathrm{m}}\right) \quad (5)$$

$$u_3'' = \ddot{q}_{3,\mathrm{m}} - k_{\dot{q}_3}\left(\dot{q}_3 - \dot{q}_{3,\mathrm{m}}\right) - k_{q_3}\left(q_3 - q_{3,\mathrm{m}}\right) \quad (6)$$

The reference trajectories are adjusted to compensate for the effect of faults. Block diagram of the reconfiguration mechanism and RTM is illustrated in Fig. 4.

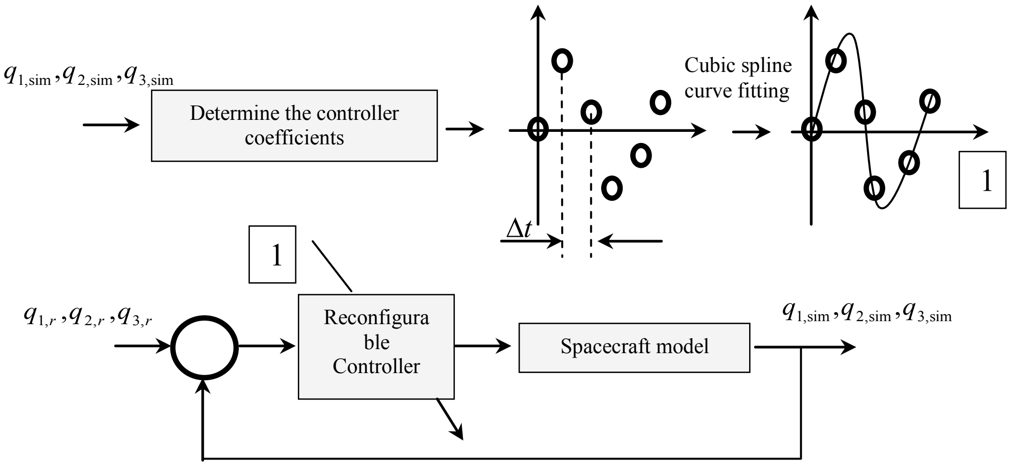

Figure 2. Block diagram of the reconfiguration mechanism (controller reconfiguration).

The modified reference trajectories are determined at fixed Δt intervals. Then, a cubic spline passes through these points to make the modified reference trajectories smooth functions of time. The simulation loop is repeated several times until the stopping criterion is satisfied. The output of Fig. 4 is the smooth curves (modified reference trajectories) produced by cubic splines.

3.3 Goal of the AFTC

The goal of the AFTC is defined as follows:

Determine the controller coefficients/modified reference trajectories such that the following cost function is minimized:

$$J = \int_{t_s}^{t_f} \left(\mathbf{q}_r - \mathbf{q}\right)^T \left(\mathbf{q}_r - \mathbf{q}\right) dt \qquad (7)$$

t_f and t_s are the final and settling times, respectively. Therefore, the goal of the AFTC is to minimize the distance between the faulty system response ($\mathbf{q}$) and the reference trajectories ($\mathbf{q}_r$).

In order to compare the performance of the proposed controller reconfiguration and RTM, a numerical example will be presented in the next section.

4 Simulation

The actuation system consists of six thrusters (without considering hardware redundancy), that are placed in opposite directions and each thruster is capable of producing maximum 50 N variable thrust. The effective moment arm of all thrusters is one meter along the principal body axis. However, the configuration of the thrusters is such that the thrust forces (T_1-T_2), (T_3-T_4) and (T_5-T_6) produce net moments about the first, second and third principal axes, respectively (Fig. 5). The direction of arrows shows the direction of the forces produced by the thrusters.

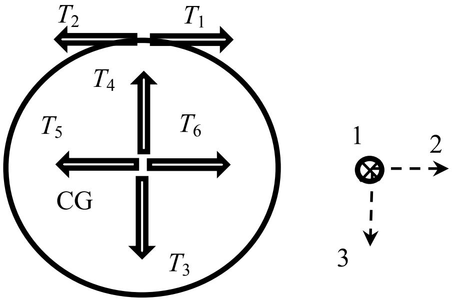

Figure 5. Thruster configuration (CG: Center of gravity).

Therefore, the relation between control torques and thrust forces can be obtained according to the following equations:

$$u_1^+ = T_1, u_1^- = -T_2 \qquad (8)$$

$$u_2^+ = T_3, u_2^- = -T_4 \qquad (9)$$

$$u_3^+ = T_5, u_3^- = -T_6 \qquad (10)$$

The superscripts + and – show the positive and negative control moments, respectively.

It seems that the thrusters T_3, T_4, T_5 and T_6 pass through CG. However as stated in the previous paragraph, they have a moment arm of one meter along the first body axis.

Physical properties [13], initial conditions and controller parameters are presented in Table 1.

It is assumed that the faults occur at $t_{fault} = 0$, $t_s = 70\,\text{s}$ and $t_f = 100\,\text{s}$. The reference trajectory has the following profile:

$$\mathbf{r} = \left[\phi_r(t), \theta_r(t), \psi_r(t)\right] = \left[0.1t, 0.1t, -0.1t\right] \qquad (11)$$

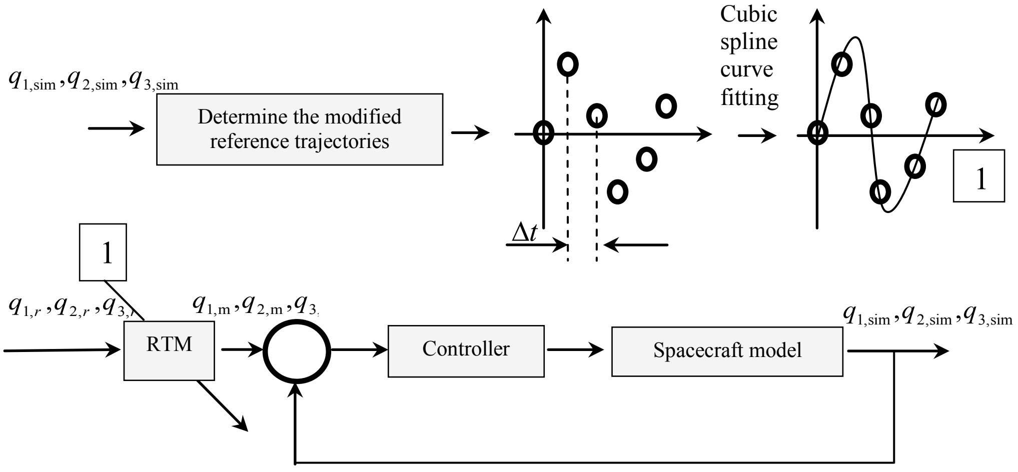

Figure 4. Block diagram of the reconfiguration mechanism and the RTM.

Table 1. Simulation parameters.

Moments of inertia $(\mathrm{kg.m}^2)$	**Initial condition s** (deg)	**Initial condition s**	**Controller coefficients**	
$I_1 = 449.5$	$\phi(0) = 15$	$\omega_1(0) = 0$	$k_{q_1} = 1$	$k_{\dot{q}_1} = 0.1$
$I_2 = 264.6$	$\theta(0) = 10$	$\omega_2(0) = 0$	$k_{q_2} = 1$	$k_{\dot{q}_2} = 0.1$
$I_3 = 312.5$	$\psi(0) = -5$	$\omega_3(0) = 0$	$k_{q_3} = 1$	$k_{\dot{q}_3} = 0.1$

The fault scenario considered in this paper is the reduction in the actuator region [14]. The post-fault actuator region is assumed to be:

$$\mathrm{sat}_n(u_i) = \begin{cases} u_i & \text{if } -u_{\max,n} \le u_i \le u_{\max,n} \\ u_{\max,n} & \text{if } u_i > u_{\max,n} \\ -u_{\max,n} & \text{if } u_i < -u_{\max,n} \end{cases} \quad (12)$$

$u_{\max,n}$ is the new actuator region obtained after the occurrence of actuator fault in the system.

The new actuator regions are determined according to the following relation:

$$u_{\max,n} = a u_{\max} \quad (13)$$

a is the actuator effectiveness coefficient and is a value between 0 and 1. Therefore, the maximum and minimum reductions in actuator region will be 100% (failure mode) and 0% (safe mode), respectively. It is assumed that after the fault, the values of actuator effectiveness coefficients are given in Table 2:

Table 2. Effectiveness coefficients.

a_1	a_2	a_3	a_4	a_5	a_6
1	1	1	1	0.1	0.1

Therefore, it is assumed that the thrusters T_5 and T_6 can produce 5 N-m moments about the third body axis.

Interior-point is used as the solver. The stopping criterion is considered to be 500 simulations. The parameters of this solver are the default values considered in MATLAB 2011a.

The values of cost functions obtained by the proposed methods are presented in Table 3:

Table 3. Cost functions.

	Controller reconfiguration	**RTM**
J	8.75E-11	7.44E-4

It is shown that in comparison to RTM, controller reconfiguration has made the cost function smaller and therefore, the faulty system response ($\mathbf{q}$) closer to the reference trajectories ($\mathbf{q}_r$).

The Euler angles corresponding to the controller reconfiguration and RTM are illustrated in Figs. 6 and 7, respectively.

A comparison of Figs. 6 and 7 shows the better performance (quality of response) of controller reconfiguration in comparison to RTM. The main reason is that the proposed controller reconfiguration has more variables to modify the closed-loop system behavior. Thrust profiles are also illustrated in Figs. 8 and 9.

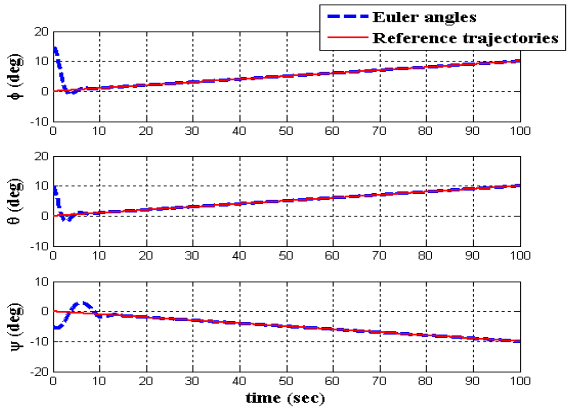

Figure 6. Time histories of Euler angles (controller reconfiguration).

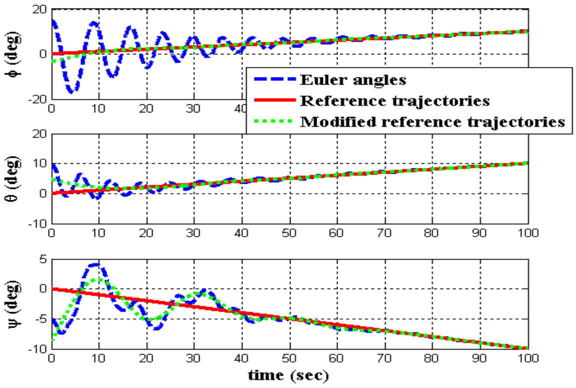

Figure 7. Time histories of Euler angles (RTM).

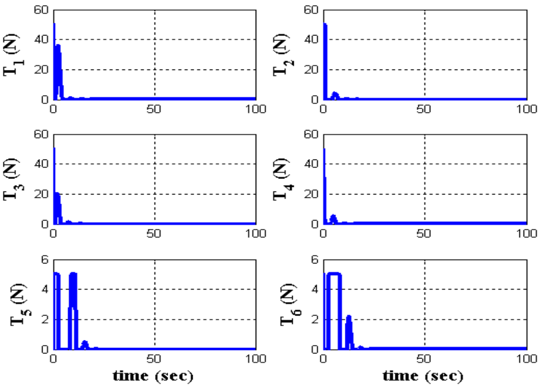

Figure 8. Thrust profiles (controller reconfiguration).

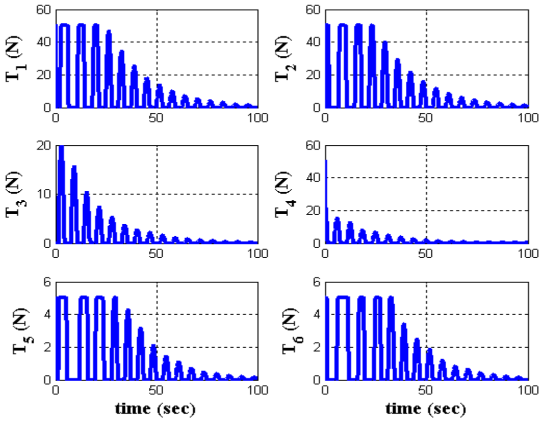

Figure 9. Thrust profiles (RTM).

Another important point is the energy consumption. Figs. 8 and 9 show that the proposed controller reconfiguration not only has a better performance from a response quality point of view but also from an energy consumption view point.

Finally, the controller coefficients for the proposed controller reconfiguration are illustrated in Fig. 10:

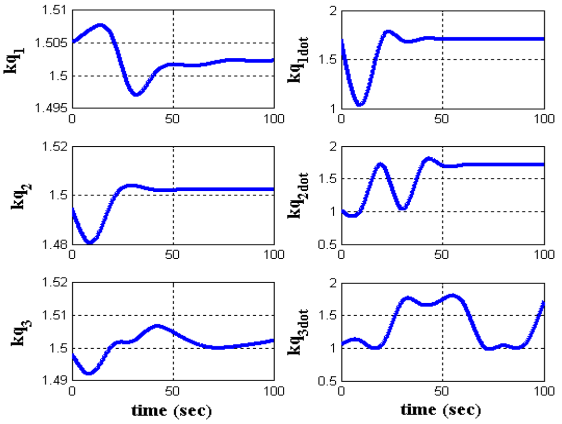

Figure 10. Time histories of controller coefficients (Controller reconfiguration).

It should be noted that the initial values considered for the controller coefficients (controller reconfiguration) are the same as Table 1. The initial values considered for the modified reference trajectories (RTM) are the same as the reference trajectories and $\Delta t = 10$ s.

5 Summary

Reference trajectory management and controller reconfiguration are two methods to design active fault tolerant controllers. Each method is capable of handling faults and retaining the pre-fault performance efficiently. Comparing the performance of these two methods, under the same conditions is an interesting problem. In this paper, a controller reconfiguration and a reference trajectory management were proposed to design active attitude fault tolerant controllers for a faulty spacecraft. It was shown that under the same conditions, the proposed controller reconfiguration shows better performance than the proposed reference trajectory management. The main reason is that the proposed controller reconfiguration has more variables to modify the closed-loop system behavior. As a future work, it is possible to consider analytical methods to have a better comparison between the two approaches.

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