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Multi-objective optimization in graceful performance degradation and its application in spacecraft attitude fault-tolerant control

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ABSTRACT

Reducing the burden of the remaining actuators through decreasing the performance gracefully is an important field in active fault tolerant control. According to the literature, two important points have been identified in the works considering graceful performance degradation: 1) using single-objective optimization, 2) assuming an engineering insight into the performance of the faulty system. This paper has two contributions: First, it is shown that in some cases, single-objective optimization may not be able to provide a satisfactory solution for the problem. Second, a new systematic and general method is proposed to remove the need for the engineering insight. The proposed method is based on multi-objective optimization. Attitude tracking of a faulty spacecraft is considered as a case study. Simulation results show the advantages of the proposed methodology.

1. Introduction

Active fault tolerant control (AFTC) is an important research area in automatic control from theoretic and practical points of view. The essential components of this type of controller are fault detection and diagnosis (FDD), reconfigurable controller and a reconfiguration mechanism [1,2]. Almost an uncountable number of papers, books, and reports have considered AFTC. Among the references, [1] has prepared a comprehensive study and literature review about this subject. Spacecraft attitude fault tolerant control has been considered deeply in the literature. Among the various papers, [3] and [4] are two recent studies that have considered this problem. Ref. [5] is a recently published review paper that has considered the FTC literature in spacecraft attitude control problem.

Reference trajectory management (RTM) is one of the components of general AFTC structure [1]. The main responsibility of RTM is to adjust/modify the reference trajectories to make the faulty system stable while preserving the pre-fault performance as much as possible [6]. There are several papers that have studied the effects of RTM on the performance and stability of the post-fault system ([7–9] and [10]). According to these works, RTM has been able to deal with the actuator faults/failures efficiently.

Graceful performance degradation (GPD) is a methodology based on accepting some performance degradation in favor of fulfilling the mission objectives. This definition was introduced for the first time by [11] and then extended by [12–17] and finally, [18].

References [11–14] and [15] have assumed an engineering insight into the performance of the faulty system. Ref. [16] has not considered the burden of actuators in their problem. A quadratic cost function has been defined to optimize the performance of the controller, by forcing the post-fault system to track the nominal (fault-free) trajectories. Performance degradation and actuator saturation have been considered simultaneously by [17]. A variable (degradation factor) has been introduced to model performance degradation. Constrained optimization is then used to find this variable. Zhou et al. [18] have reduced the conservatism of this method by considering a matrix of degradation factors.

A review of the previous works in the GPD field shows two important points: First, utilizing single-objective optimization and second, assuming an engineering insight into the performance of the faulty system.

This paper has two contributions: First, it is shown that single-objective optimization may fail to provide a desirable solution for the GPD problem. The situation gets worse when there is not an engineering insight into the performance of the faulty system, which is often the case for multiple faults. Second, a general and systematic procedure is proposed to implement the GPD concept on a wide range of systems. This technique annihilates the need

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Nomenclature

$\mathbf{q} = [q_0, q_1, q_2, q_3]$	quaternion vector	
$\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]$	angular velocity vector	rad/s
(u'_1, u'_2, u'_3)	normalized control inputs	s^{-2}
(I_1, I_2, I_3)	principal moments of inertia	$kg\,m^2$
(u_1, u_2, u_3)	control moments acting on the spacecraft	$kg\,m^2\,s^{-2}$
t_{fault}	fault occurrence time	s
t_s	settling time	s
J^*	optimal solution in the Pareto optimal set	
$\mathbf{r} = [\phi, \theta, \psi]$	Euler angles	rad
$\boldsymbol{\xi}$	vector of design variables (decision variables)	
PM	vector of performance measure (objective functions)	
$\boldsymbol{\lambda}$	weighting coefficient vector	
$\boldsymbol{\alpha}$	contractive coefficient vector	
t_{final}	final time	s
$\mathbf{n}_s$	number of times that the actuators saturate	
Tr	thrust force	$kg\,m\,s^{-2}$

for an engineering insight into the performance of the faulty system.

In order to demonstrate the capabilities of the proposed approach, attitude tracking of a rigid spacecraft subject to multiple actuator faults will be considered as the case study. Three different scenarios of randomly generated faults will be taken into account. The advantages of the proposed method will be demonstrated, and it will be shown that single-objective optimization may fail to provide a reasonable solution.

This paper consists of the following sections: Section 2 presents general preliminaries. Spacecraft dynamics and control as well as, single and multi-objective optimization are the topics of this section. Sections 3 and 4 discuss the RTM structure and stability analysis, respectively. Section 5 presents the main idea of this paper. Finally, the proposed method is used to design a GPD based AFTC for the attitude tracking of a rigid body spacecraft (section 6).

2. Preliminaries

2.1. Spacecraft dynamics and control

The rigid spacecraft rotational motion in the principal coordinate system is governed by the following equations [19]:

$$\dot{q}_0 = 0.5(-\omega_1 q_1 - \omega_2 q_2 - \omega_3 q_3)$$

$$\dot{q}_1 = 0.5(\omega_1 q_0 + \omega_3 q_2 - \omega_2 q_3)$$

$$\dot{q}_2 = 0.5(\omega_2 q_0 - \omega_3 q_1 + \omega_1 q_3)$$

$$\dot{q}_3 = 0.5(\omega_3 q_0 + \omega_2 q_1 - \omega_1 q_2)$$

$$\dot{\omega}_1 = \left(\frac{I_2 - I_3}{I_1}\right)\omega_2\omega_3 + u'_1$$

$$\dot{\omega}_2 = \left(\frac{I_3 - I_1}{I_2}\right)\omega_1\omega_3 + u'_2$$

$$\dot{\omega}_3 = \left(\frac{I_1 - I_2}{I_3}\right)\omega_1\omega_2 + u'_3$$

The relation between control torques and inputs are given by Eqs. (1), (2) and (3):

$$u'_1 = u_1/I_1 \tag{1}$$

$$u'_2 = u_2/I_2 \tag{2}$$

$$u'_3 = u_3/I_3 \tag{3}$$

The upper and lower bounds of the control inputs are restricted according to the following saturation function:

$$\operatorname{sat}(u_i) = \begin{cases} u_i & \text{if } -u_{\max} \le u_i \le u_{\max} \\ u_{\max} & \text{if } u_i > u_{\max} \\ -u_{\max} & \text{if } u_i < -u_{\max} \end{cases}$$

The following relation always exists between quaternions [19]:

$$q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$$

The advantage of constraint equation is that for three known elements of the quaternion vector, the other element can be determined. This also leads to a less complicated controller design, since the number of controlled outputs becomes three (instead of four) and therefore, the number of inputs and outputs become equal.

The following vector is considered as the output vector:

$$\mathbf{y} = [q_1 \quad q_2 \quad q_3]^T$$

Clearly, the second time derivative of this vector contains the control inputs. Consequently, the *total relative degree* becomes $2 + 2 + 2 = 6$, which is equal to the number of states ($[q_1, q_2, q_3, \omega_1, \omega_2, \omega_3]$). Therefore, no internal dynamics exists, and input–output linearization can be used easily [20].

Obtaining the second time derivative of the output vector will result in the following equations:

$$\ddot{q}_1 = -\frac{1}{4}q_1\sum_{i=1}^{3}\omega_i^2 + \frac{1}{2}(G_1 q_0\omega_2\omega_3 - G_2 q_3\omega_1\omega_3 + G_3 q_2\omega_1\omega_2) + \frac{1}{2}(q_0 u'_1 - q_3 u'_2 + q_2 u'_3)$$

$$\ddot{q}_2 = -\frac{1}{4}q_2\sum_{i=1}^{3}\omega_i^2 + \frac{1}{2}(G_1 q_3\omega_2\omega_3 + G_2 q_0\omega_1\omega_3 - G_3 q_1\omega_1\omega_2) + \frac{1}{2}(q_3 u'_1 + q_0 u'_2 - q_1 u'_3)$$

$$\ddot{q}_3 = -\frac{1}{4}q_3\sum_{i=1}^{3}\omega_i^2 + \frac{1}{2}(-G_1 q_2\omega_2\omega_3 + G_2 q_1\omega_1\omega_3 + G_3 q_0\omega_1\omega_2) + \frac{1}{2}(-q_2 u'_1 + q_1 u'_2 + q_0 u'_3)$$

where:

$$G_1 = (I_2 - I_3)/I_1,\; G_2 = (I_3 - I_1)/I_2 \quad \text{and} \quad G_3 = (I_1 - I_2)/I_3.$$

These equations are in a suitable format. Therefore, feedback linearization can be easily employed to transform them into the following linear time-invariant (LTI) form:

$$\ddot{q}_1 = u''_1$$

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