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Optimization of control parameters based on genetic algorithms for spacecraft attitude tracking with input constraints

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ABSTRACT

This paper studies the attitude tracking control problem for rigid spacecraft with input constraint, parameter uncertainties and harmonic disturbances. By combining a nonlinear proportional-derivative (PD) control, a novel adaptive control strategy whose parameters are optimized by a genetic algorithm with hyperbolic tangent function is proposed to guarantee the globally asymptotic convergence of the attitude tracking process. In particular, the nonlinear proportional-derivative (PD) control term is utilized to achieve better tracking performance with shorter settling time and smaller/no overshoot. By considering the strong connection between the complex controller parameters and the tracking performances, the genetic algorithms are adopted to determine the optimal set of controller parameters and optimal value of time acted as fitness goals of the algorithm. Finally, the effectiveness of the proposed control method is shown by the numerical simulations.

1. Introduction

Accurate and reliable attitude stabilization is always one of the most important problems in spacecraft control system design. However, the unknown environment disturbances, spacecraft uncertainties and input constraints, etc., further increase the complexity and difficulty in control scheme design. During past decades extensive studies on spacecraft attitude tracking control have been carried out, and some control-inspired approaches, such as optimal control [1–3] and sliding-mode control [4,5], have been successfully applied to the spacecraft attitude tracking control problem. In particular, adaptive control has been shown to be an effective scheme in investigations of a wide class of non-linear systems [6–8] in which unknown parameters exist. In most of these articles, either norm bounded or energy bounded disturbances are taken explicitly into consideration. A common feature for all the aforementioned papers is that they do not address the transient performance with short settling time and small overshoot for attitude variables. Furthermore, although the above research can obtain satisfactory results in attitude tracking for spacecraft control, they also do not consider control input saturation in the controller design, which is an important problem related to spacecraft control and cannot be ignored in practical applications. If the issue of saturation constraint is not considered in controller design, the controller output will deviate from input of the controlled object, which would cause closed-loop system performance deterioration or even entire system instability if the control input of the system is saturated. Hence, globally stable control schemes that explicitly consider input constraint have elicited considerable interest. Consequently, it is very necessary to take the input constraints into account during the attitude controller design [9–17]. For the linear system, predictive control [18] and optimal control [19] have been applied to treat problems with input constraints, whereas the control system must be determined a priori and no disturbances are considered yet. The problem of input constraints for aerospace application is considered in Ref. [20], in which an anti-windup control scheme was proposed for the large-angle attitude control of a spacecraft under actuator saturation. Ref. [21] applied a backstepping technique to the nonlinear flight system in the absence of input constraint first, and then a command filter was employed to compensate the effect of the control signal rate constraint. In Ref. [22] a designed to control the spacecraft attitude under input saturation. However, its control scheme lacks generality to non-linear systems. Therefore, the formulation in this paper uses continuous hyperbolic tangent functions, rather than the typical switching functions, to guarantee boundedness of all closed-loop signals, convergence of the angular velocity error, and conformity with saturation limits. On the other hand, a class of disturbances with unbounded energy is presented,

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which is a finite linear combination of constant and sinusoidal functions with known frequencies but unknown amplitudes and phase angles. Thus, an internal model is designed. It is implemented to solve the harmonic disturbances.

In almost all literatures mentioned so far, a linear operator should be introduced to isolate the uncertain parameter in the inertia matrix for the use of adaptive control law, since the conventional matrix multiplication is not commutative [23]. Specifically, in this research, we will consider a more interesting problem where a rigid spacecraft involves inertia matrix parameter uncertainty. We will make use of a new matrix product, called semi-tensor product (STP) and denoted by $\ltimes$, which has been proposed in [24], and the inertia parameters are estimated by an adaptive algorithm. The advantage of using the STP to deal with the parameter uncertainty is that the STP can overcome the non-commutative shortage of the conventional matrix product.

A novel control technique, known as the composite nonlinear feedback (CNF), is proposed for a class of second order linear systems to improve the transient performance of the closed-loop system in [25]. The idea is extended to a class of nonlinear systems in [26–28]. The key idea of CNF control is to smoothly alter the damping ratio of the closed-loop system by this important idea, we design a nonlinear proportional-derivative (PD) type feedback controller, which constitutes another part of the overall control strategy, for the spacecraft attitude tracking system. In this way, an excellent tracking response with short settling time and small overshoot for the attitude vector, represented by Modified Rodrigues Parameter (MRP), is achieved. The simultaneous treatment of all of these factors is a challenging task for an attitude tracking control system to meet the high-precision tracking requirement and desired control performance during the missions.

The controller includes a number of design parameters, and there is a certain relationship among the coupling parameters. Selection of the parameters determines the performance of the controller. The controller parameters' optimization design [29–36], mostly depended on the experience of designers to select the design parameters. Genetic algorithms are a class of non-traditional stochastic methods solving complex optimization problems of the real world [37–39]. They are optimization techniques that artificially simulate the gradual adaptation of natural chromosomes in the quest of producing better and more suitable individuals. In this paper, the design parameters are given for the optimized variables and the optimal time is given for the optimized objectives, with the output moment as the constrain condition. A genetic algorithm is used to solve for the optimized controller parameters. This simple, effective method does not rely on the designer's experience.

The main contributions of this paper are as follows: (1) the new matrix product, i.e., semi-tensor product is applied to deal with attitude tracking control problem of rigid spacecraft; (2) explicit accounting for the problem of input constraint; (3) the designed control scheme does not rely on the exact knowledge of the inertia parameters and the magnitudes and phase angles of harmonic disturbances. Only the frequency components of harmonic signals are required; (4) the nonlinear PD feedback control part of the overall adaptive control law can achieve better transient performance with shorter settling time and smaller/no overshoot for the attitude variables; (5) a genetic algorithm is applied to deal with the optimized controller parameters.

The organization of this paper is presented as follows. The mathematical model of a spacecraft tracking dynamics described by MRP vector is introduced in Section 2. And the control objectives also stated and presented some standard assumptions, preliminaries of the semi-tensor product, the attitude control and disturbance rejection problem. In Section 3, an adaptive control law is proposed by combining the semi-tensor product, the CNF control method and the internal model, followed by means of Lyapunov stability theory, it is proved theoretically that the designed control law can assure that tracking error converges to an arbitrarily small neighborhood around zero. Then, a genetic algorithm is designed to cope with for the optimized controller parameters in Section 4. Numerical simulations are presented to demonstrate the effectiveness and feasibility of the proposed schemes in Section 5. Finally, conclusions are given in Section 6.

2. Control problem for spacecraft

2.1. Attitude kinematics and dynamics

As is known to all, spacecraft attitude tracking control objective is affected by many external factors, but the spacecraft attitude description is the foundation of spacecraft kinematics equation. In this technical note, the Modified Rodrigues Parameter (MRP) is used to describe the rigid body attitude. Define the rigid body attitude and the attitude angular velocity of the rigid spacecraft body frame with respect to the inertia axis frame as $\sigma \in R^3$ and $\omega \in R^3$, respectively. Similarly, with the attitude trajectory of desired axis frame with respect to the inertia axis frame, the respective denotations are $\sigma_d \in R^3$ and $\omega_d \in R^3$. In this paper, the desired body attitude signal, defined by σ_d, ω_d and $\dot{\omega}_d$, and it can be assumed known or measured. The dynamic equation of a rigid spacecraft can be modeled as [40]

$$J\dot{\omega} + \omega^{\times} J\omega = u + d, \tag{1}$$

where $J \in R^{3\times 3}$ is the constant and positive-definite symmetric inertia matrix of the spacecraft. $u \in R^3$ and $d \in R^3$ are the control torques and the Harmonic disturbance, respectively. Define an arbitrary vector $\kappa = [\kappa_1, \kappa_2, \kappa_3]^T \in R^3$, the notation $\kappa^{\times}$ denotes a skew-symmetric operator acting on the vector κ [40].

The attitude error σ_e and the attitude angular velocity error ω_e of the body frame with respect to the desired axis frame are modeled as [41]

$$\omega_e = \omega - R(\sigma_e)\omega_d, \tag{2}$$

$R(\sigma_e)\omega_d$ is the projection of ω_d in the body frame, $R(\sigma_e)$ is the transformation matrix from the desired axis frame to the body frame.

The error attitude kinematic equation is introduced as follows [42]:

$$\dot{\sigma}_e = G(\sigma_e)\omega_e, \tag{3}$$

where

$$G(\sigma_e) = \frac{1}{2}\left(\frac{1-\sigma_e^T\sigma_e}{2} I_3 + \sigma_e^{\times} + \sigma_e\sigma_e^T\right). \tag{4}$$

Substituting (2) into (1), the error attitude dynamic equation can be modeled as

$$\begin{aligned} J\dot{\omega}_e = & -\omega_e^{\times} J\omega - [J(R(\sigma_e)\omega_d)^{\times} + (R(\sigma_e)\omega_d)^{\times} J]\omega_e - [(R(\sigma_e)\omega_d)^{\times} JR(\sigma_e)\omega_d \\ & + JR(\sigma_e)\dot{\omega}_d] + u + d, \end{aligned} \tag{5}$$

Based on the conditions above, we assume the following:

Assumption 1. The spacecraft inertia matrix J appearing in Eq. (5) is unknown and can be expressed as

$$J = J_0 + \Delta J, \tag{6}$$

where J_0 is the nominal part of J and ΔJ is the uncertain part of J.

Remark 1. Similar to [23], if the inertia matrix J has parameter uncertainty, there exists an unknown vector δ with dimension