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Time efficient spacecraft maneuver using constrained torque distribution

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ABSTRACT

This paper investigates the time efficient maneuver of rigid satellites with inertia uncertainty and bounded external disturbance. A redundant cluster of four reaction wheels is used to control the spacecraft. To make full use of the controllability and avoid frequent unload for reaction wheels, a maximum output torque and maximum angular momentum constrained torque distribution method is developed. Based on this distribution approach, the maximum allowable acceleration and velocity of the satellite are optimized during the maneuvering. A novel braking curve is designed on the basis of the optimization strategy of the control torque distribution. A quaternion-based sliding mode control law is proposed to render the state to track the braking curve strictly. The designed controller provides smooth control torque, time efficiency and high control precision. Finally, practical numerical examples are illustrated to show the effectiveness of the developed torque distribution strategy and control methodology.

1. Introduction

The satellites which provide rapid multi-target acquisition, pointing and tracking capabilities have attracted a great deal of interest due to its importance in space missions [1]. There have been a few launched satellites with the agile attitude maneuver ability such as Pleiades, OrbView-3 and WorldView. These satellites play increasingly important roles in imaging, disaster emergency tasks and other areas.

One of the key characteristics of agile satellites is high precision [2,3] and time efficient [4,5] large angle maneuvering, and the corresponding design problem [6,7] has been addressed extensively in the existing literature. In [8], the authors analyzed the time optimal reorientation problem for an inertially symmetric rigid spacecraft with independent three-axis control, and pointed out that eigenaxis rotation is not the time optimal reorientation path. However, in many practical cases eigenaxis rotation can be regarded as a sub-optimal solution. In [9], the authors followed the work of [8] and revealed that whether eigenaxis maneuver is optimal is dependent on the definition of admissible control. In particular, when the magnitude of the input vector was constrained while the control direction was left free, the eigenaxis maneuver was indeed the time-optimal solution. In [10], Steyn investigated the near-minimum-time eigenaxis rotation problem. The constant ratio of the Euler vector components and body angular rates during the eigenaxis rotation was used to achieve the balance of minimum time and minimum control effort when using reaction wheel. The physical constraints such as wheel torque and wheel speed were considered and the constrained tracking curve was developed. To track the predesigned curve, a "bang-bang" control strategy was adopted. Wie considered the actuator limit and sensor saturation and developed a feedback control logic [11] for the same problem. This work was extended in [1]. The proposed cascade-saturation control logic has been widely used for large-angle rapid multitarget acquisition and pointing maneuvers. Besides this type of PD controller, sliding mode control [12], backstepping [13], adaptive control [14] or the combination of these strategies [15] have also been employed to deal with the model uncertainty and external disturbance.

The control signal calculated by the various control law should be realized by using either the external environmental influences such as gravity, magnetic torques [16], fuel consuming thrusters [3,17] or internal momentum exchange devices [18–20]. The first category of the actuators are applied in the early space missions or employed as accessory appliances in the attitude control system, and the thrusters are rarely installed on agile satellite for attitude control due to the limited onboard propellant. Thus reaction wheels become an ideal actuators. Bayard [21] and Ismail [22] investigated the three reaction wheel configuration from view of control torque, momentum storage, power requirements and pointing accuracy and found the intuitively reasonable orientation which tended to favor the body axis. However, an extra skew

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Nomenclature

$\| \boldsymbol{a} \|_2$	2-norm of a vector $\boldsymbol{a}$
$\boldsymbol{x}_{tol}$	lower bound of $\boldsymbol{x}$, smaller than which will be regarded as zero in computer
$\boldsymbol{\alpha}$, $\boldsymbol{\alpha_{max}}$	angular acceleration (deceleration) of the satellite and its maximum, rad/s^2
λ	optimization parameter
τ_a	maximum allowable output torque of each flywheel, N m
$\tau_w(\tau_{wi})$	output vector comprised of the output of each RW τ_{wi}, N m
$\boldsymbol{\omega}$	angular velocity of the satellite, rad/s
ω_{ideal}	ideal angular velocity during maneuver, rad/s
ω_{max}	maximum allowable angular velocity of the satellite, rad/s
ω_{wi}	angular velocity of the ith wheel, rad/s
$\boldsymbol{A_{rw}}$	installation matrix of the reaction wheels
$\boldsymbol{e}$	velocity error between the real angular velocity and the ideal velocity, rad/s
f_0	safety factor
$\boldsymbol{h}(h_i)$	momentum vector comprised of the wheels momentum h_i, N ms
$\boldsymbol{H}$	control angular momentum, N ms
H_a	maximum allowable angular momentum for each flywheel, N ms
$\boldsymbol{H_T}$	satellite's total angular momentum, N ms
$\boldsymbol{J}$	satellite's moment of inertia without the consideration of wheels, kg m^2
J_{ii}, J_{max}	satellite's principle inertia and its maximum principle value, kg m^2
$\boldsymbol{J_T}$, $J_{T\,max}$	satellite's total moment of inertia and its maximum value, kg m^2
$J_w(J_{wi})$	moment of inertia of the (ith) reaction wheel, kg m^2
q_0, $\boldsymbol{q_v}$, $\boldsymbol{q}$	scalar part and vector part of the unit quaternion $\boldsymbol{q}$
$\hat{\boldsymbol{q}}_{\boldsymbol{v}}$	unit vector of $\boldsymbol{q_v}$
r_h	ratio between the output angular momentum and allowable angular momentum
r_τ	ratio between the output torque and allowable torque
R_{wi}	ith reaction wheel
$\boldsymbol{T_e}$, $T_{e\,max}$	total external torque and its upper bound, N m
$\boldsymbol{T}$, $\boldsymbol{T_{max}}$	actuated control torque and its maximum value, N m
$\boldsymbol{U}$, $\boldsymbol{U_c}$	desired control torque and the command control torque, N m
$\boldsymbol{V}$, $\boldsymbol{V_1}$	candidate Lyapunov function

wheel is usually added to form the common redundant cluster of four reaction wheels system, which will be employed for attitude control in this paper, to provide redundancy and enhance control capability. Except the reaction wheel's configuration, the steering law, how to map a required control torque from a given control law to the set of reaction wheel motor torque effectively, also plays an important role in attitude control. Basically, the torque can be directly distributed from the satellite body frame level to the RW level for a three wheels' case. Unfortunately, when having four or more wheels, the solution will not be unique unless additional requirements are added. Schaub investigated the classical L_2 norm solution for minimum torque distribution and pointed out that it was instantaneous power-optimal [23]. Hogan focused on the wheel saturation and addressed the attitude control problem with continuous momentum dumping [24]. Dov proposed an L_∞ torque distribution method to enhance the controllability and avoid frequent unload [4]. However the distribution input and output are all acceleration, which is not the general scenery of the attitude control. Motivated by this observation, the main contribution of this paper can be stated as follows:

1. A generalized L_∞ torque distribution method is proposed to minimize maximum output torque distributed to the RWs. Thus the physical saturation and frequent unload are avoided. This method is applicable to arbitrary redundant configuration, including the standard type of three orthogonal wheels plus extra skew one.
2. A novel quaternion vector part based ideal tracking curve is designed using the generalized L_∞ torque distribution method, thus the Euler-angle based kinematics differential equation of [5] is greatly simplified.
3. A quaternion-based sliding mode control law is proposed to render the state to track the braking curve strictly. By tracking this pre-designed braking curve, the time efficient maneuver is achieved.

The remaining part of this paper is organized as follows. Section 2 formulates the design problem and objective of this paper. Section 3 presents a new torque distribution method, and the tracking curve design problem by using the developed control allocation method is considered in Section 4. A novel sliding mode control law is synthesized in Section 5. Section 6 gives numerical simulation results with various practical initial conditions. Finally, the conclusion is discussed in Section 7.

2. Problem formulation

2.1. Reaction wheel dynamics

Considering an attitude control system, suppose that all the wheels have a unified setting, and they are balanced rotating bodies, that means the wheel's rotation do not affect the system mass property. In this setting, the momentum of each wheel can be described as:

$$h_i = J_{wi}\omega_{wi} \tag{1}$$

where h_i represents the ith wheel's angular momentum, J_{wi} is the ith moment of inertia around its rotation axis, ω_{wi} is the angular velocity of the ith wheel. Since all the wheels are in the same setting, J_{wi} can be written as J_w.

In Eq. (1), the additional angular momentum resulted from the rotation of satellite is ignored, since the angular velocity of the satellite is quite smaller compared to the wheel's velocity. Although ω_{wi} in practice may achieve 7000 rps or larger, it always has an upper bound, thus h_i also has an upper bound.

As a kind of momentum exchange device, wheels provide control torque through accelerating or decelerating, and the control torque of the ith wheel can be denoted as

$$\tau_w(i) = -\frac{d}{dt}h_i \tag{2}$$

2.2. Satellite dynamics

The installation matrix of the wheels is defined as $\boldsymbol{A}_{rw}$, then the