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Extended State Observer based robust attitude control of spacecraft with input saturation

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ABSTRACT

This paper addresses the problem of robust optimal control of spacecraft attitude stabilization in the presence of parametric uncertainties, external disturbances and actuator saturation simultaneously. As a stepping stone, an Extended State Observer (ESO) is developed to estimate and compensate the specified uncertainties including actuators' misalignments and parametric uncertainties while ensuring uniformly ultimately bounded estimation error in the sense of finite-time stability. Then, with the reconstructed information, an inverse optimal Control Lyapunov Function (CLF) approach is developed to guarantee asymptotic stability of the closed-loop system, such that an optimal/minimum performance index can be achieved. The associated stability proof is constructive and accomplished by the development of a novel Lyapunov function candidate. Furthermore, with the concept of input–output linearization of dynamics transverse to zero dynamic manifold, a rapid exponential stabilization CLF based optimal control scheme is investigated by utilizing the quadratic programming technique to restrain the actuator saturation. Simulation results are presented to illustrate the performance of the proposed schemes.

1. Introduction

Recent decades have witnessed many important developments related to the design of attitude control laws for spacecraft stabilization, and several inspiring approaches have been proposed, such as optimal control [1,2], nonlinear feedback control [3], adaptive control [4], sliding mode control [5], and robust control or their integrations [6,7]. Generally speaking, part or most of previous works can achieve the attitude or pointing stabilization in the presence of uncertainties in certain degree, but some optimization problems such as time optimal, fuel/energy optimal/minimum, or some other optimal performance indexes, cannot be considered at the same time. Due to its inherent robustness and optimality with respect to nonlinearity and uncertainty, the nonlinear optimal control is a potential approach to solving the nonlinear attitude control problem. While the advent of the steady-state Hamilton–Jacobi–Bellman (HJB) equation, the relationship between stability and optimality becomes a consistent issue in the optimal stabilization problem [8], but this is still an open problem due to the difficulty of solving the associate HJB function. In Ref. [1], Sharma and Tewari proposed a HJB formulation for spacecraft attitude maneuvers to drive a nonlinear optimal control law. State-dependent Riccati equation (SDRE) method was also used to solve the optimal attitude control problem [9], although only sub-optimality and local stability can be guaranteed. Given this, a class of globally asymptotically stable feedback control laws for a non-symmetric rigid body has been further investigated to achieve optimal characteristics in Ref. [10].

Inverse optimal control technique is an alternative approach to derive optimal feedback control laws for spacecraft attitude control problem. Robust inverse optimal-control approach [11] circumvents the task of solving the HJB partial differential equation and results in an optimal controller with respect to a set of cost functions. For robust inverse optimal approach, the knowledge of Control Lyapunov Function (CLF) is very important for the designer, and it can solve HJB equations associated with a meaningful cost and a stable control law for an auxiliary nonlinear system. In Ref. [12], a novel robust inverse optimal nonlinear attitude control law was developed for the regulation of a rigid spacecraft. In Ref. [13], the attitude tracking control problem for spacecraft with external disturbances was addressed using the robust inverse optimal control method, associated with CLF. Pukdeboon [14] presented two optimal sliding mode control laws, in which CLF approach was used to solve the nonlinear optimal attitude tracking control problem. Luo [15] addressed the attitude tracking control problem with external disturbances and an uncertain inertia matrix by means of adaptive CLF method. Recently, Ames [16]

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Nomenclature

$\boldsymbol{\rho}$	Modified Rodrigues Parameters
$\boldsymbol{\omega}$	angular velocity of a spacecraft
$\boldsymbol{\rho}^{\times}$	a skew-symmetric matrix
$\boldsymbol{J}$	inertia matrix of the spacecraft
$\boldsymbol{u}$	total torque vector
$\boldsymbol{\tau}$	torque produced by reaction wheels
$\boldsymbol{d}$	external disturbances
$\boldsymbol{J}_0$	defined symmetrical matrix
$\Delta\boldsymbol{J}$	uncertainty of $\boldsymbol{J}$
$\boldsymbol{D}$	distribution/configuration matrix
$\boldsymbol{D}_0$	nominal value of configuration matrix
$\Delta\boldsymbol{D}$	uncertainty of configuration matrix
$\boldsymbol{z}_1, \boldsymbol{z}_2$	new coordinate transformation
$\boldsymbol{Z}_1, \boldsymbol{Z}_2$	outputs of the extended state observer
$\boldsymbol{E}_1, \boldsymbol{E}_2$	observer errors
$\beta_i,\ i = 0, 1, \ldots, 4$	observer gains
$\boldsymbol{\Omega}$	positive define matrix
$\sigma_{\min}(\bullet),\ \sigma_{\max}(\bullet)$	minimum and maximum singular value of the specified matrix
T_0, T_1, T_2	finite time intervals
$a, b, c, \alpha, k, \lambda_1$	positive constant to be designed
γ, k_1	controller gains
$L_f(\bullet)$	operator for Lie derivative
Ψ	performance index function
$\zeta(\boldsymbol{x}),\ R_u(\boldsymbol{x})$	nonnegative functions for all $\boldsymbol{x} \neq 0$
$\boldsymbol{y}$	attitude based output (vector relative 2 degree)
$\boldsymbol{Z}$	zero dynamic surface of the attitude control system
$\boldsymbol{\mu}$	a feed-forward item
$\boldsymbol{z}$	zero dynamics states
$\boldsymbol{\eta}$	defined transverse variable
$\boldsymbol{P}, \boldsymbol{Q}$	positive definite symmetrical matrix
c_1, c_2, c_3	positive constants
ϵ	positive constant satisfying $0 < \epsilon < 1$
$m(\boldsymbol{\eta})$	optimal solution of min-norm controller
d_1	small positive variable
p_1	large constant that penalizes the offset of RES-CLF constraints
T	sampling time
$\Vert \bullet \Vert$	2-norm for a vector

Acronym

ESO	Extended State Observer
CLF	Control Lyapunov Function
HJB	Hamilton–Jacobi–Bellman
RES-CLF	rapid exponentially stabilizing CLF
SDRE	State-Dependent Riccati Equation
ZD	Zero Dynamic
CLF_IOC	CLF based inverse optimal control law
RESCLF_QPC	RES-CLF and quadratic programing based optimal controller
PID	Proportional-Integration-Derivative

Subscript

v	vector
eq	equivalent value
min	minimum
max	maximum

Superscript

T	vector or matrix transpose
-1	matrix inverse
$+$	pseudo-inverse of matrix
$\bullet$	derivative of the variable

demonstrated that a class of modified rapid exponentially stabilizing CLF (RES-CLF) that enforce rapid exponential convergence to the zero dynamic surface can be used to achieve the stability of the periodic orbit in the full-order dynamics, thereby extending the stabilizing controllers by utilizing point-wise minimum norm method [17], which is optimal with respect to a cost function. To date, the design of the controller assuring convergence to the zero dynamics manifold has been developed in several ways [18–20], but the feedback controllers were usually used to render the zero dynamics sufficiently attractive to asymptotic stability.

To actively compensate for the so-called uncertainty and/or disturbance, Extended State Observer (ESO) has been considered as an effective way [21]. The key idea of ESO is that system uncertainties and disturbances are considered as an added or extended state of the system, and then all the states including the extended one will be estimated accurately and quickly by ESO. In Ref. [22], the problem of attitude control for a spacecraft model with inertia uncertainty and external disturbance has been investigated by utilizing ESO and further combined with an adaptive updating law. For the antenna pointing control of a large flexible satellite system, ESO was developed to estimate the total uncertain of the system in Ref. [23]. Additionally, Reference [24] proposed a new robust optimal control strategy for flexible attitude tracking maneuvers in the presence of external disturbances, through the method of CLF incorporating with ESO. While, in the sense of convergence of ESO, there are few rigorous proofs for the stabilization of the closed-loop system. Reference [25] tried to address the convergence of a nonlinear high-gain extended state observer even in the presence of uncertainties, but the asymptotical stability was achieved under some restrictive assumptions. And he stability analysis when the ESO is incorporated with CLF is still lacking.

Another important problem encountered in practice is that of actuator saturation. The occurrence of actuator saturation will subsequently reduce performances and even destabilize the closed-loop system, if the system is not equipped with an appropriate control scheme to reject the issue of saturation. As such, several solutions/methods have been proposed to deal with actuator saturation constraints, such as inverse tangent-based function [26], explicit saturation function [27], anti-windup scheme [28] and some other ways [29,30] as a direct way. That is to say, the functions/methods can be imposed directly on the controllers such that the control signals are produced within the specified limitations. Additionally, the actuator saturation issue also can be dealt with in the process of control allocation as an indirect way. For instance, some practical actuators' constraints were added in the quadratic programming scheme, in order to obtain an optimal control effort with the rejection of actuator saturation [31,32] utilizing control allocator.

The main contribution of this paper is the design of a class of novel control algorithms for spacecraft stabilization system that takes into account control input saturation explicitly, assures fast and accurate response, and achieves effective compensation for the effect of external disturbances and parametric uncertainties, and has the following properties: 1) An ESO is investigated to estimate all the states of the system, which is used to compensate for specified total uncertainty. And also the uniformly ultimately bounded stability in finite time of ESO is guaranteed via a rigorous Lyapunov analysis. 2) An inverse optimal CLF approach is presented