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On novel adaptive saturated deployment control of tethered satellite system with guaranteed output tracking prescribed performance

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ABSTRACT

In this paper, a novel model-free adaptive saturated control approach for deployment of the tethered satellite system (TSS) is developed based on time- and event-triggered mechanisms with consideration of the tether length constraint, actuator saturation and unknown external disturbance. Firstly, an appropriate output prescribed performance function is selected to quantitatively analyze the transient and steady-state performance of the deployment control system. Then, a strict-feedback system is established via an output transformation based on which two new model-free adaptive saturated control schemes are developed. Compared with the existing works, the primary advantage of the proposed approach is that the output tracking performance of the TSS can be guaranteed a priori with excellent disturbance rejection capability. Meanwhile, it is the first time that the event-triggered prescribed performance control scheme is proposed both in theoretic and application views, which dramatically reduces the frequency of controller updating and makes the corresponding designed schemes more applicable in practice. Finally, two group of illustrative examples are employed to validate the effectiveness of the proposed control approach.

1. Introduction

The past few decades have witnessed the burgeoning development in the space tethered satellite system (TSS), due to its great potential applications in the space exploration including debris capture, debris removal and tether assisted observation, to name a few [1–6].

Wherein, deployment control of the TSS has gained extensive attention owing to the fact that effective deployment control law is the prerequisite to make the TSS practically applicable [2,3]. For example, Kumar and Tan applied inverse optimal technique to develop a nonlinear optimal control scheme for the TSS based on the tether offset variations [7]. Considering the input constraints, Ma and Sun reported an adaptive sliding mode control scheme for tethered satellite deployment [8]. With the purpose of suppressing libration of the TSS, the controller proposed by Yousefian and Salarieh was only applied to make the main satellite attitude maneuver in a circular orbit [9]. Different from the aforementioned control schemes, Yu et al. proposed an analytical deployment control law for the flexible TSS, which is easily achievable in practical implementation [10]. However, the uncertainties involved in the TSS dynamics and external space disturbance make it very challenging to obtain a precise analytical solution. In [11] and [12], Liu et al. and Wen et al. proposed two different tether tension control laws, respectively, based on full states and partial states of the TSS.

Generally, the tether length constraint and actuator saturation are inevitably encountered in practical applications of the TSS, which has been evolved as a fairly knotty and challenging control problem for deployment control of the TSS. To tackle this problem, various potential control methods have sprung up in the existing works. For example, optimal control methods including model predictive control method were applied to develop the corresponding deployment control laws for the TSS in [13–15]. Although effective, the iterative numerical optimizations increase the computational burden, which makes it difficult to implement in practice. To avoid this problem, Ma et al. developed a novel dynamic adaptive saturated sliding mode controller for the deployment control of the TSS based on modified dimensionless dynamic model [16]. Moreover, various effective sliding mode control schemes were furthered investigated in the deployment control of the TSS in [17–19]. In order to account explicitly for the tension constraint efficiently, Wen et al. attempted to develop an analytical feedback control scheme by constructing a special saturation function [20]. However, it is assumed that the deployment is active, wherein, the

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tether can be reeled in or out actively [21]. In this case, the overshooting phenomenon exists during the tether deployment, which requires complex active mechanism to reel in or out the tether. To avoid this drawback, Liu et al. proposed two effective passive tether deployment schemes, i.e., continuous control law and pulsewidth pulse-frequency (PWPF) modulation control law, based on well-designed non-overshooting trajectories [21].

However, two problems should be considered. The first one is the transient and steady-state performance (e.g., convergence rate, overshoot, undershoot, steady tracking accuracy, etc.) of the TSS. In [21], pole assignment method was applied to guarantee the transient performance (like overshoot and convergence rate) of output-feedback linearized model of the TSS theoretically and effectively. However, the linearization errors and space perturbations are not considered. Thus, an achievable quantitative structure to *simultaneously* address the transient and steady-state performance with consideration of the nonlinear model, external disturbance and unmodeled dynamics (like friction in deployment/retrieval mechanisms) deserves further investigations. The second one is the unremitting updates of actuators in the aforementioned works including the discrete PWPF modulation control scheme. Owing to the fact that the existing tether deployment control schemes are devised based on time-triggered control mechanism, it requires the actuators to response to the desired input command very quickly. This is not applicable for that there often exists a large time delay between the response and command input during the missions such as the length change of the tether. Thus, how to lower the frequency of actuator updating also deserves investigations.

For the first problem, attributed to Bechlioulis and Rovithakis' work, the prescribed performance including the transient and steady-state performance of the nonlinear systems can be guaranteed a priori by involving the performance into the controller design with appropriate performance functions [22]. This control method was further investigated in flexible joint robotic system [23], hypersonic flight vehicle system [24], uncertain large-scale nonlinear systems [25], and postcapture flexible spacecraft [26]. But to the authors' best knowledge, no attempts are reported to develop prescribed performance deployment controller for the TSS in the existing works. For the second problem, the time-triggered control schemes may lead to unaffordable energy consumptions for the controller updating, which makes the devised deployment schemes not easily achievable for the TSS in practice. In order to solve this problem, event-triggered control strategy has been widely applied to develop discontinuous-time control schemes by replacing the time-triggered control strategy [27–29]. For example, Shi et al. developed an event-triggered neural control scheme for singular systems with consideration of the input quantizations and the employed application in inverted pendulum control demonstrated that the frequency of controller updating was reduced dramatically [30]. Lu et al. proposed an event-triggered proportional-integral (PI) controller with supplementary adaptive dynamic programming based compensation in load frequency control, which significantly alleviates the computational burden brought out by the controller updating [31]. But event-triggered deployment control scheme of the TSS has not been reported in the existing works.

The foregoing discussions motivate our study. In this paper, we attempt to develop an effective and applicable adaptive saturated control approach for the TSS deployment with consideration the tether length constraint, the actuator saturation and the external disturbance. To the best knowledge of the authors, it is the first time that the event-triggered deployment control scheme with guaranteed output tracking performance is proposed for the TSS. In detail, the contributions of this work are twofold.

$\mathscr{C}1$. It is the first time that the adaptive saturated deployment control approach of the TSS with output prescribed tracking performance is proposed, wherein, the tether length constraint is primely handled by constructing an appropriate performance function. Moreover, the transient and steady-state performance of the TSS is simultaneously guaranteed with excellent disturbance rejection capability.

$\mathscr{C}2$. It is the first time that the event-triggered strategy is introduced in the prescribed performance control approach both in theoretical and application views. Compared with the existing works, the prominent advantage is that the actuator updating is determined by the predefined events rather than the time sequences, which dramatically reduces the updating frequency of actuator and eases the operation intensity of physical devices embedded in the TSS.

The remainder of this paper is organized as follows. Section 2 shows the problem statement with description of the dynamics of the TSS. Two novel adaptive saturated prescribed performance control schemes of the TSS based on time/event-triggered strategies are given in Sec. 3. Illustrative simulations of the proposed control schemes are organized in Sec. 4 and some conclusions are drawn in Sec. 5.

1.1. Notations

T, $\|\bullet\|$, $|\bullet|$, $\sigma(\bullet)$ are the vector transpose, the Euclidean norm of a vector, the absolute value of a real number, and the eigenvalue of a nonsingular matrix, respectively. $\mathbb{R}^n$, $\mathbb{R}^{n+}$ represent the set of n-dimensional real numbers and n-dimensional positive real numbers, respectively. $\mathbb{N}$, $\mathbb{N}^+$ denote the set of nonnegative integers and positive integers, respectively. $\vec{\mathbf{1}} \in \mathbb{R}^n$ is the n-dimensional column vector of all ones. $\boldsymbol{I}$ is the identity matrix with appropriate dimensions.

2. Problem formulation

According to [16], the geometric representation of the TSS is demonstrated in Fig. 1. To simplify the dynamic description, the following coordinate frames are defined: $OXYZ$ is the Earth-centered inertial frame where the origin is collocated with the earth center of mass, and the OX, OZ pointing to the spring equinox and north pole, respectively. $O_1X'Y'Z'$ denotes the orbital coordinate frame with O_1X', O_1Z' being the directions of the orbital velocity and the point towards the center of the earth, respectively. Employing right-hand triad can generate O_1Y' (O_1 is the mass center of the TSS). $O_1X''Y''Z''$ represents the tethered frame with OZ'' pointing to the subsatellite along the tether.

The considered TSS involving a mother satellite and a subsatellite is from the YES2 project with the mass of the mother satellite and the subsatellite being 6530 kg and 12 kg, respectively [32]. To simplify the subsequent research, it is assumed that the deployment of the TSS is regulated by the tether tension and the thrusters mounted on the subsatellite. And the tether remains inextensible, straight and stiff all the time [16].

2.1. Dynamics of the tethered satellite deployment system

Based on the aforementioned description, the dynamic model of the TSS is expressed by [16]

$$\overline{m}\ddot{l} - \overline{m}l\left(\left(\dot{\psi}^2 + (\dot{\theta}+\omega)^2\cos^2(\psi)\right) + \omega^2\left(3\cos^2\psi\cos^2\theta - 1\right)\right) = -u_t + d_t, \tag{1a}$$

$$\overline{m}l^2\cos^2\psi\ddot{\theta} + 2\overline{m}(\dot{\theta}+\omega)l^2\cos^2\psi\left(\dot{l}/l - \dot{\psi}\tan\psi\right) + 3\overline{m}\omega^2 l^2\sin\theta\cos\theta\cos^2\psi = u_\theta + d_\theta, \tag{1b}$$