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Research article

# Robust inertia-free attitude takeover control of postcapture combined spacecraft with guaranteed prescribed performance

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ABSTRACT

In this paper, a robust inertia-free attitude takeover control scheme with guaranteed prescribed performance is investigated for postcapture combined spacecraft with consideration of unmeasurable states, unknown inertial property and external disturbance torque. Firstly, to estimate the unavailable angular velocity of combination accurately, a novel finite-time-convergent tracking differentiator is developed with a quite computationally achievable structure free from the unknown nonlinear dynamics of combined spacecraft. Then, a robust inertia-free prescribed performance control scheme is proposed, wherein, the transient and steady-state performance of combined spacecraft is first quantitatively studied by stabilizing the filtered attitude tracking errors. Compared with the existing works, the prominent advantage is that no parameter identifications and no neural or fuzzy nonlinear approximations are needed, which decreases the complexity of robust controller design dramatically. Moreover, the prescribed performance of combined spacecraft is guaranteed a priori without resorting to repeated regulations of the controller parameters. Finally, four illustrative examples are employed to validate the effectiveness of the proposed control scheme and tracking differentiator.



## 1. Introduction

The past decades have witnessed the great development of on-orbit servicing with the sharply increasing number of launching satellites. However, many non-functioning satellites owing to the lack of attitude and orbit control ability become a threat to the other healthy on-orbit satellites, which has been a risky and challenging task for the future space development.

At present, a promising way to cope with this risk is capturing the non-functioning satellites by manipulators mounted on a service spacecraft. Commonly, it is expected that the non-functioning spacecraft can be recovered from failure owing to the fact that many useful devices can be recycled for economic consideration [1]. For instance, in order to extend the operational lifetime of non-functioning satellites, Project SMART-OLEV [2] and FREND [3] were executed to provide them with propulsion, navigation and guidance services. In order to capture the on-orbit target spacecraft, the space robot as a feasible way has attracted considerable attention in recent years [4,5]. In Ref. [6], nonlinear optimization technique was utilized to design a class of manoeuvres for grasping a target satellite by a space manipulator. Impact dynamics and vibration suppression of a flexible space robot capturing an object were studied in Refs. [7,8]. Flores-Abad and Ma investigated an optimal control strategy for a space manipulator to have minimal impact to the base satellite during the capturing operation [9]. Aghili studied the optimal control of robot capturing a tumbling satellite with unknown parameters [10]. Floresabad et al. developed an efficient control strategy to obtain an optimal time and final pose of the tumbling target by a space manipulator [11]. After the capture, a surrogate control system provided by service spacecraft will takeover control the target spacecraft with

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loss of attitude and orbit control ability. In terms of attitude control of combined spacecraft, tethered space robot with a three-link manipulator was applied to capture the target spacecraft and an adaptive sliding mode controller was devised to stabilize the combined spacecraft in Ref. [12]. Huang et al. investigated the attitude takeover or coordinated control of combined spacecraft with space robot in the presence of external disturbance torque in Refs. [13–16,18]. Similarly, an adaptive attitude control scheme based on contraction theory was proposed for combined spacecraft with a large captured object subject to uncertainty and external disturbance in Ref. [19].

However, for the postcapture attitude control of combined spacecraft, two problems are often encountered. The first one is the unmeasurable state variables under limited observation resources of combined spacecraft, which makes the full-state-based control methods ineffective like in Refs. [13–17]. From the practical engineering perspective, the angular velocity of spacecraft is difficult to measure in the complex space environment [20–22]. The second one is the inherent unknown nonlinearity of combined spacecraft. Due to the lack of sufficient information of the target spacecraft, the inertial property of combination is difficult to determine. In this case, it is difficult to establish an accurate dynamic model, which increases the difficulty of stabilization and robust control of combined spacecraft.

For the first problem, state observer as an efficient way is widely utilized to obtain the unmeasurable states like a finite-time state observer developed for a group of flexible spacecraft in Ref. [21]. He et al. applied a high-gain observer to effectively estimate the relative velocity between two neighboring spacecrafts with consideration of measurement noise and external disturbance in Ref. [22]. Although the unknown state variables can be obtained by the state observers, commonly, the system model information is often required in the construction of relevant observers such as Luenberger state observer in Ref. [23], fuzzy state observer in Refs. [24,25] and finite-time state observer in Ref. [26], to name a few. So these state observers are model-based, which are not practically applicable for postcapture spacecraft in the presence of unknown inertial properties and uncertain dynamics. To overcome such limitations, tracking differentiator (TD) works as an effective model-free tool to extract the continuous and differential information from discontinuous or measurement signals with random noise in numerous engineering applications [27]. In the meanwhile, TD is also a crucial link to active disturbance rejection control (ADRC) developed by Han [27], and has gained extensive attention in the estimation of unavailable differential information of signals in Refs. [28–30]. Unlike the traditional model-based linear or nonlinear state observers mentioned above, TD is independent on the system dynamic model, consequently, the parameters of TD are easy to regulate in practice [30]. In Ref. [31], a higher-order tracking differentiator was proposed to estimate the unknown state variables of hypersonic vehicle. However, it is sensitive to measurement noise, which is not applicable in practice. Thus, the design of low-complexity TD with a computationally simple structure and fast convergence rate is always an open issue in the field of observation. Meanwhile, investigations of low-complexity TD for combined spacecraft with limited expensive computational resources also deserve further attention.

For the second problem, many parameter identification and nonlinear approximation methods are adopted for spacecraft in the existing works. The online momentum-based estimation method was used to estimate the unknown inertial property of combined spacecraft after grasping the unknown debris in Ref. [32]. Instead of estimating the inertial parameters, Leeghim et al. applied neural network technique to approximate the coupled nonlinear functions with unknown moment of inertia in Ref. [33]. The similar handling ways appeared in the tracking control of spacecraft in Refs. [34,35]. Huo et al. investigated the fuzzy finite-time attitude tracking control of spacecraft by using fuzzy logic systems to approximate the unknown nonlinear functions in Ref. [36]. However, complicated procedure of parameter identification and nonlinear approximation with neural network or fuzzy logic system for unknown target spacecraft will consume many expensive computational resources. In this sense, the combined spacecraft will not be stabilized in time. Moreover, the associated attitude control schemes are efficient only within the compact set where the capabilities of the universal neural or fuzzy approximators hold. Thus, how to surmount the demerits brought by parameter identification and nonlinear approximation deserves further investigation for combined spacecraft.

Apart from the aforementioned problems, another crucial issue associated with attitude control of combined systems is the transient (such as convergence rate, overshoot and undershoot) and steady-state tracking performance. In practice, ensuring a high fidelity transient and steady-state tracking performance of combined spacecraft is very challenging in the coexistence of uncertainty and external disturbance. Attributed to Bechlioulis and Rovithakis' work [37], a new control design and synthesis methodology was developed, in which the transient and steady-state performance is quantitatively characterized by a user-specialized prescribed performance function (PPF). Then, this method was further exploited in Refs. [38–45]. Specifically, a low-complexity robust model-free control scheme was developed without any prior knowledge of the dynamic model for pure feedback nonlinear system in Refs. [39,40], which reduces the computational burden brought by neural or fuzzy approximations and parameter identification methods. And this method was extended to multiple input multiple output feedback linearizable systems in Ref. [46], which provides a potential alternative way for tackling the second problem mentioned above. However, the full-state information is required in the construction of relevant model-free control schemes in Refs. [39,46], which is not easily achievable for practical systems like spacecraft. Thus, robust prescribed performance control with partial-state information deserves further investigations under limited observation resources.

Motivated by the foregoing discussions, this paper aims at developing a robust inertia-free prescribed performance control scheme for the combined spacecraft with unmeasurable states subject to unknown inertial property and external disturbance torque. To the authors' best knowledge, there exist very few works on the robust inertia-free control of (combined) spacecraft with guaranteed prescribed performance. Compared with the existing works, our contributions are twofold

- $\mathscr{C}_1$ A novel finite-time-convergent tracking differentiator (HFTCD) based on hyperbolic tangent sigmoid transfer function is developed to obtain the unmeasurable angular velocity of combined spacecraft. The proposed tracking differentiator is computationally simple and is not sensitive to measurement noise in the robust controller design of combined spacecraft with high estimation accuracy. Meanwhile, the fast convergence property of tracking differentiator guarantees that the unmeasurable angular velocity can be obtained with fast convergence rate.
- $\mathscr{C}_2$ A robust inertia-free prescribed performance control scheme of combined spacecraft is first proposed with consideration of unmeasurable states, unknown inertial property, and external disturbance torque. Compared with the existing works, the prominent advantage of the proposed control scheme is that the transient and steady-state performance of combined spacecraft is guaranteed a priori by stabilizing the filtered state variables without resorting to repeated regulations of the controller parameters, which decreases the complexity and difficulty of robust controller design dramatically. Meanwhile, different from the existing work [46], we extend the full-state-based prescribed perfor-