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Anti-disturbance attitude control of combined spacecraft with enhanced control allocation scheme

Jianzhong QIAO, Zhibing LIU, Wenshuo LI *

School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

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Abstract In this paper, we propose a novel anti-disturbance attitude control law for combined spacecraft with an improved closed-loop control allocation scheme. More specifically, a saturated approach is adopted to guarantee the global asymptotic stability under control input saturation. To enhance the robustness of the system, a nonlinear disturbance observer is constructed to compensate the disturbances caused by inertial parameter uncertainty and unmodeled dynamics. Next, the quadratic programming algorithm is used to obtain an optimal open-loop control allocation scheme, where both energy consumption and actuator saturation have been considered in the allocation of the virtual control command. Then, a modified closed-loop control allocation scheme is proposed to reduce the allocation error under the actuator uncertainty. Finally, stability analysis of the closed-loop system with the proposed allocation scheme is provided. Simulation results confirm the effectiveness of the proposed control scheme.

1. Introduction

Combined spacecraft refers to a class of cooperative or non-cooperative target spacecraft that are combined together to accomplish certain space tasks such as space operation and space debris clearance. Combined spacecraft is gaining popularity due to its potential capacity in space missions that are beyond the capability of a single spacecraft. As one of the key technologies for combined spacecraft systems, high-precision and reliable attitude control has attracted increasing attentions among researchers throughout the world. For orbiting combined spacecraft, the attitude dynamics are strongly nonlinear and vulnerable to multiple sources of disturbances, including external disturbances, parametric uncertainties and modeling errors. Up to now, considerable results have been published on attitude stabilization control of the combined spacecraft. However, most of the existing results have not taken the actuator constraints into account, which may lead to actuator saturation and cause serious discrepancies between the expected and actual control signals. Moreover, an assembled spacecraft control system is over-actuated with redundant actuators. Therefore, it is important to study the problem of how to properly allocate the control command among the actuators. A major challenge in the control allocation problem

* Corresponding author.
E-mail address: wslibuaa@126.com (W. LI).

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is how to deal with the uncertainties caused by the misalignment of actuators and the measurement error of torque magnitudes. The difficulties mentioned above have significantly complicated the design of combined spacecraft attitude control system, especially when all these aforementioned issues are considered simultaneously.

Accounting for constraints such as input saturation in the controller design has been the focus of tremendous research efforts over the past decade (see Refs. 1–10 and references therein). Several inspiring and effective approaches, such as variable structure control, adaptive control and optimal control, have been developed to address the identified challenges. Specifically, a saturation control scheme has been proposed in Ref. 11 for an under-actuated rigid spacecraft, where a non-standard representation of the attitude, allowing the general motion to be decomposed into two rotations, is adopted to facilitate the derivation of control law. An attitude stabilization scheme has been developed by Wallsgrove and Akella in Ref. 12, where hyperbolic tangent functions are incorporated to guarantee a smooth control input. With the controller designed in Ref. 12, we can adjust the sharpness of the control input by tuning a set of parameters, thus to a large extent avoiding the chattering phenomenon which is widely recognized as a critical disadvantage of the variable-structure method. A nonlinear bounded control has been developed in Ref. 13 by employing the back-stepping procedure and an inverse tangent-based tracking function. Due to its simplicity and effectiveness, the Proportional-Derivative (PD) or PD-like control methods have also been extensively investigated. Incorporating a standard hyper-tangent function, a simple saturated PD control scheme has been developed in Ref. 14, where it is guaranteed that the attitude of rigid spacecraft is asymptotically stable regardless of the initial condition. As we all know, multiple sources of disturbances widely exist in spacecraft systems and will cause performance degradation or even instability of the control system.

The above mentioned control approaches, however, have not explicitly taken disturbance rejection into consideration. Popular approaches to anti-disturbance control include disturbance attenuation and disturbance compensation. The former is to design a feedback control law in order to reduce the effect of disturbances to a certain degree, while the latter constructs an observer to derive a disturbance estimate which is then used for feed-forward compensation. Among the disturbance compensation methods, a novel Nonlinear Disturbance Observer Based Control (NDOBC) method has been proposed in Ref. 15 for robotic manipulators and in Ref. 16 for missile control. The disturbance estimation error was guaranteed to converge to zero asymptotically under the condition that the disturbance varies slowly. A novel composite controller has been proposed in Ref. 17 to deal with multiple disturbances, where the DOB is used in the inner loop for disturbance compensation and the H_∞ controller is adopted in the outer loop to attenuate the effect remaining disturbances as well as disturbance estimation errors. The disturbance observer based composite intelligent learning control scheme has been proposed in Refs. 18,19 and shown to achieve enhanced performance in the presence of unknown nonlinearity. In Refs. 20,21, the disturbance observer based approach has been combined with the game theoretical approach to achieve optimal performance.

The combination of multiple spacecraft has inevitably introduced more control effectors than what is actually required, which makes the combined spacecraft an over-actuated system. It is known that the performance of an over-actuated system can be improved if the actuator redundancy is properly exploited. The control allocation (CA) technique is a common method to deal with the problem of control redundancy, where the command signals generated by the baseline controller are allocated to different actuators in order to meet the requirement of controller design. The existence of redundant actuators will certainly provide extra flexibility to the design of control system. An increase in the number of redundant control effectors, however, will lead to a more complicated design of control system. The issue control allocation is especially important when the actuator fails or when the control surface is damaged. In such cases, it is required that the control commands be reallocated among the remaining healthy control actuators to maintain an acceptable performance. Control allocation problem has been intensively studied in the past decades, with typical solutions including daisy chaining,[22] direct allocation,[23,24] linear or nonlinear programming-based optimization,[23] and dynamic control allocation.[24–26] In Ref. 27, a pseudo-inverse method has been proposed, and a fixed-point based algorithm has been implemented and tested in a benchmark spacecraft model. In Ref. 28, a mini-max control allocation scheme is developed to meet the multiple conflicting objectives simultaneously by finding a 'Pareto' optimal solution. In Ref. 29, a control scheme has been proposed, where the real-time structure is fed back and the structural load constraints are taken into consideration in the design of control allocation scheme. In Ref. 30, constrained optimization based control allocation scheme has been employed to achieve desired torque without violating the specified constraints on monitored load points. The method proposed in Ref. 30 adopts the dynamic control allocation approach, where the resulting allocation scheme also depends on the allocation of the previous sampling instant. This method penalizes the actuator rates and can therefore be seen as an extension of the regular quadratic programming based allocation scheme. In Ref. 31, a novel robust control allocation approach has been developed in the presence of partial or complete loss of control effects. Most of the above mentioned control allocation schemes, though successfully applied to certain tasks, are all open-loop schemes which have not fully exploited the real-time information. Among the few studies on the closed-loop allocation scheme, a detailed comparison has been made in Ref. 32 between open-loop and closed-loop performance for sixteen control allocation schemes. However, in Ref. 32, stability issues have not been considered for the closed-loop system when the control allocation scheme is combined with the baseline controller. Having recognized this, Zhang and Chen proposed a closed-loop control allocation scheme in Ref. 33 based on the cascaded generalized inverse method, and provided sufficient and necessary conditions for the satellite system to be stable. In Ref. 34, a novel saturated PD control law incorporated with Closed-Loop Control Allocation (CLCA) has been proposed by Hu and Li with guaranteed asymptotic stability of the closed-loop system.

In this paper, a novel control scheme, which combines the DisturBance Observer based Saturated Attitude Control law (SAC + DOBC) and a Modified Closed Loop Control Allocation (MCLCA) approach, is developed for attitude stabilization of the combined spacecraft. Specifically, the SAC + DOBC control law is designed to generate a virtual control