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# Nonlinear disturbance observer-based robust control for spacecraft formation flying

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This paper proposes a composed control approach by combining a nonlinear disturbance (NDO) observer and an asymptotic tracking control (ATC) for spacecraft formation flying system subject to nonvanishing disturbances. In this paper, the multiple disturbances that act on spacecraft from space environment and uncertain mass are considered as unknown external disturbances. The proposed NDO is used to estimate and compensate for the disturbances through feedforward. Stability of the composite closed-loop system is provided using Lyapunov theory. It is shown that the proposed composite controller can significantly enhance disturbance attenuation ability and achieve robust tracking in the presence of the parameter uncertainty and external disturbances. Simulations results are included to demonstrate the effectiveness of the proposed control scheme. Robust dynamic performance and position control accuracy are effectively improved.



## 1. Introduction

Spacecraft formation flying (SFF) has been extensively studied and implemented for the distribution of a large spacecraft functionality to numerous smaller spacecraft to enhance future space mission. SFF is growing, significant technological challenges remain within the realm of control design for formation maintenance and formation configuration [1]. The current literature related to SFF mainly focus on the control problem of relative position based on linear and nonlinear dynamics models. For the past decade SFF literature largely has involved the control of SFF system using the linearized spacecraft relative motion dynamics called the Clohessy–Wiltshire (CW) equations [2]. Initial work on SFF involved rendezvous of a pair of spacecraft using linear control techniques to regulate relative positions [3]. Nonlinearity of the differential gravitational acceleration, eccentricity of the reference orbit, and the Earth's oblateness are the three most important perturbations that breakdown the circular orbit solutions to CW equations [4].

A significant challenge in the control design is to develop a formation maintenance controller that will enable the spacecraft to maintain a desired relative orbit with minimum propellant expenditure. Controller designs based on the linearized equations of motion, the CW [2] require extra fuel consumption and may not achieve a design goal required for specific formation flying performance along with long duration and large separation between two spacecraft. Gosh and Bosse [5] examined linear and nonlinear LEO (Low Earth Orbit) formation control methodologies, one of each type, for the purpose of evaluating them from a propellant budget, thrust level and error dynamics point. In spacecraft formation flying problem, the distance between spacecraft is not necessarily small, and the model errors to be compensated through control. A better choice is to use a nonlinear representation, which should be valid large distances between spacecraft, reducing model errors. To further reduce the model errors in SFF, external disturbances or perturbations described above and parametric uncertainties should be considered in controller design. However, robust control for uncertain nonlinear systems with unknown disturbances of SFF is a challenging problem [6]. Disturbances including external disturbances, unmodeled dynamics and parameter uncertainties widely exist in SFF [7]. External disturbances including the Earth oblateness, atmospheric drag, and solar radiation pressure cause a drift of both the relative positions of the spacecraft and the formation center [6,8].

In the last decades, several studies on the state-dependent Riccati equation (SDRE) [9,10] have been done for spacecraft formation flying problem as a method of nonlinear regulation. To design this control, the nonlinear system must be written in a pseudo-linear form (state-dependent coefficient, SDC), where the system and input matrices are state dependent. Nonlinear perturbation modelings can be added to nonlinear relative motion dynamics for an SDRE but unknown external disturbances cannot be considered in a conventional SDRE design procedure. Qing et al. [11] proposed a nonlinear controller for disturbances rejection and col-

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lision avoidance for SFF where a nonlinear model with $J_2$ perturbation and atmospheric drag is described. Based on the SDRE, a finite-time nonlinear tracking controller is developed with a compensatory internal mode control law is added to eliminate disturbances. Several other approaches also have been proposed for control of SFF, which include linear control and nonlinear control methods that can be adaptive or nonadaptive. In [6,12–14], sliding mode control techniques have been employed to attain formation control of a leader–follower configuration. Schalandbusch and Kristiansen [15] addressed the problem of the state feedback translational motion control of a spacecraft formation through a modified sliding surface controller using variable gains and $I^2$ action for disturbance rejection. Ye et al. [16] proposed a modified robust control law incorporated with the ESO (Extended State Observer) to eliminate the chattering phenomenon and reduce the conservation of the controller. In [7,17–20], nonlinear disturbance observer (NDO) based control has been employed as an effective disturbance attenuation control strategy to estimate unknown disturbances and compensate for them through feedforward. Wei and Guo [21] proposed composite disturbance-observer-based control and terminal sliding mode control for a class of multiple-input–multiple-output (MIMO) continuous non-linear systems subject to disturbances by combining the disturbance-observer-based control (DOBC) with terminal sliding mode (TSM) control. Chen et al. [22] derived a new class of nonlinear PID controllers for nonlinear systems using a nonlinear generalized predictive control approach. Wang and Wu [20] proposed a composite control approach by combining NDO and feedback linearization to attenuate the effects of parameter variations and disturbances of flexible spacecraft on attitude control accuracy and stability. The NDO can significantly improve disturbance attenuation ability and performance robustness, and is easy to combine with other traditional feedback control methods, such as, nonlinear asymptotic control, $H_\infty$, variable structure control, and sliding mode control [20,23,24].

An NDO-based control approach is proposed in this paper for spacecraft formation flying by enhancing the disturbance attenuation ability and performance robustness of the ATC (Asymptotic Tracking Control). The nonlinear relative motion dynamics with no disturbance is used for the ATC law design while the nonlinear relative motion dynamics with bounded disturbances as well as $J_2$ perturbation and atmospheric drag, which are the most dominant perturbations in LEO (Low Earth Orbit), is used for the true relative motion system of the follower spacecraft with respect the leader spacecraft. The NDO is used to estimate unknown disturbances including the effect of uncertain mass of the follower spacecraft. Then, the ATC law is designed separately from the NDO for translational tracking maneuvers of two spacecraft formation flying in the absence of unknown external disturbances. Next, the NDO is combined with the ATC via feedforward compensation as a composite controller.

Thus, there are two main contributions. Firstly, an NDO-based robust control scheme based on the nonlinear relative motion dynamics is developed taking into account the external disturbances and uncertain parameter. To the best knowledge of the author, this paper first presents a design procedure of an NDO-based robust control for a leader–follower type of spacecraft formation flying problem. The NDO is used to estimate fast varying disturbances and enhance the disturbance attenuation ability through feedforward compensation. Secondly, the asymptotic stability of the proposed control scheme is proved using Lyapunov method. Thus, this controller guarantees globally asymptotic convergence of the follower spacecraft's relative motion to any sufficiently smooth desired trajectory in the presence of external disturbances and parameter uncertainty. A numerical simulation shows the benefit in fuel cost of the proposed control in contrast to the ATC. Numerical simulation results demonstrate the effectiveness of this control scheme for a leader–follower type of spacecraft formation flying maneuver.

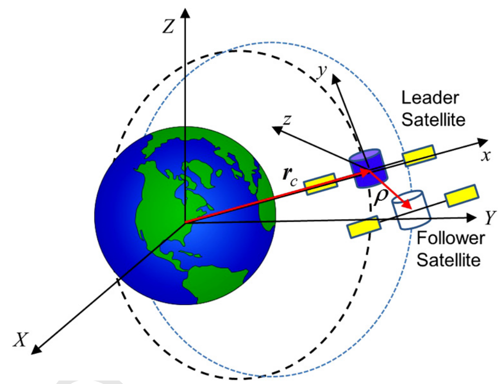


**Fig. 1.** Satellite formation coordinate system.

This paper is organized as follows. Equations of motion for the spacecraft subject to external disturbances and inertia uncertainty, and problem formulation are described in Section 2. Section 3 proposes a composite attitude tracking control scheme for spacecraft relative attitude tracking subject to external disturbances and inertia uncertainty. Simulation results are presented in Section 4 followed by conclusions in Section 5.

## 2. Leader/follower spacecraft formation mathematical model

The formation control problem which will be studied in this paper is a two-spacecraft formation. The used coordinate system is a rotating LVLH frame used to visualize the relative motion with respect to the reference or leader spacecraft as illustrated in Fig. 1. The origin of the LVLH frame is at the center of mass of the leader spacecraft where the $x$ axis points radially outward from its orbit, the $z$ axis is parallel to the orbit momentum vector in the orbit normal direction, and $y$ axis completes the right-handed coordinate system. The relative motion dynamics of the follower spacecraft is described using the Lagrangian mechanics based on the LVLH frame. The relative motion dynamics for an eccentric reference orbit is modeled by the following set of nonlinear differential equations [4]:

$$\begin{aligned}
&\ddot{x} - 2\dot{\theta}\dot{y} - \ddot{\theta}y - \dot{\theta}^2 x + \frac{\mu(r+x)}{r_d^3} - \frac{\mu}{r_c^2} = d_x + a_x,\\
&\ddot{y} + 2\dot{\theta}\dot{x} + \ddot{\theta}x - \dot{\theta}^2 y + \frac{\mu y}{r_d^3} - \frac{\mu}{r_c} = d_y + a_y,\\
&\ddot{z} + \frac{\mu z}{r_d^3} = d_z + a_z,\\
&\ddot{r}_c = r_c\dot{\theta}^2 - \frac{\mu}{r_c^2}, \quad \ddot{\theta} = -2\frac{\dot{r}_c\dot{\theta}}{r_c},
\end{aligned} \tag{1}$$

where $\mu = 3.986 \times 10^5$ km$^3$/s$^2$, $\dot{\theta} = \sqrt{\mu/r_c^3}$; $r_d = \sqrt{(r_c+x)^2+y^2+z^2}$, $\boldsymbol{\rho} = [x,\ y,\ z]^T \in \mathbb{R}^3$ and $\dot{\boldsymbol{\rho}} = [\dot{x},\ \dot{y},\ \dot{z}]^T \in \mathbb{R}^3$ are the relative position and velocity vectors of the follower spacecraft with respect to the leader spacecraft in the LVLH frame, respectively; $\boldsymbol{d} = [d_x,\ d_y,\ d_z]^T \in \mathbb{R}^3$ denotes perturbations including non-spherical shape of the Earth ($J_2$), atmospheric drag, solar radiation pressure, and solar and lunar gravity [25]; Among these perturbations, the most significant one is the second spherical harmonic in the Earth's gravity field due to oblateness (known as the $J_2$ effect); $\boldsymbol{a} = [a_x,\ a_y,\ a_z]^T \in \mathbb{R}^3$ is the control input of the follower spacecraft. In addition, $r_c$ and $r_d$ refer to the scalar radius of the leader and follower, or the chief and deputy spacecraft from