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RESEARCH ARTICLE

Neural network–based reconfiguration control for spacecraft formation in obstacle environments

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Summary

This paper proposes an adaptive formation reconfiguration control scheme based on the leader-follower strategy for multiple spacecraft systems. By taking the predesigned desired velocities and the trajectories as reference signals, a set of coordination tracking controllers is constructed by combining the reconstructed dynamic system and the neural network–based reconfiguration algorithm together. To avoid collisions between spacecraft and obstacles during the formation configuration process, the null space–based behavioral control is integrated into the control design. Since the spacecraft dynamics contains unknown nonlinearity and disturbance, it is challenging to make the system robust to uncertainties and improve the control precision simultaneously. To solve this problem, both the adaptive neural network strategy and the finite-time control theory are employed. Finally, 2 simulation examples are carried out to verify the proposed algorithm, showing that the formation reconfiguration task can be executed successfully while achieving high control precision.

KEYWORDS

coordination control, finite-time control, formation reconfiguration, modeling uncertainties, neural network, obstacle avoidance

1 | INTRODUCTION

Spacecraft formation flying (SFF) is defined as multiple spacecraft flying together with coupled dynamic states (ie, translational/rotational degrees of freedom, position, velocity, etc) in networking environments. It has become an interesting

and attractive topic over the recent decades in both the earth science and astronomy communities because of its potential merits (eg, low cost, robustness, efficiency, flexibility, etc) compared with the traditional monolithic spacecraft.¹

The typical control problems of SFF include attitude synchronization, position tracking, and formation reconfiguration. The requirements for the accurate control on relative positions and synchronization between spacecraft are the major challenges. *Attitude synchronization*, as one of the most critical issue of SFF, has been widely investigated in recent years (eg, see other works²⁻²⁰). In these literature works, several algorithms on attitude synchronization have been proposed to achieve asymptotic/exponential stability in infinite convergence time.* To pursue faster formation rearrangement capability, some *finite-time attitude synchronization* approaches have been studied.[†] However, the algorithms are infeasible for the formation reconfiguration especially in obstacle environments. The position *tracking control* is essential and significant for SFF in deep-space explorations, and a growing number of solutions have been presented (eg, see other works^{6,9,12,21-25}); however, the existing solutions can only achieve the asymptotic/exponential stability in infinite convergence time, and therefore, they cannot meet the high-precision control requirement in finite time. In addition, the aforementioned results neglect the adverse effect of obstacle/collision avoidances, which may cause the failure of tasks or even lead to disastrous consequences. Meanwhile, although *spacecraft formation reconfiguration* (SFR) can be solved by n spacecraft collaboratively, it is mainly focused on the transformation of rigid formation. It provides an alternative method to perform space operations such as interspacecraft laser communication operation, formation manoeuvres in interferometry application, passive radiometry, terrain mapping, and stereo imaging in harsh and complex space environments. The capacity of accurate control and collision/obstacle avoidance is desperately required to guarantee the security of all the spacecraft in the SFR, but only limited solutions have been presented for this problem.^{1,26-32}

Comparison with existing results. In contrast with the coordination control algorithms for SFR,^{1,26,30,31} we commit to reduce the algorithm conservatism and to achieve high control precision, which can be realized by the finite-time control theory. Comparing with the optimal control strategy without obstacle/collision avoidance,²⁷ we aim to design a new control scheme for SFR with finite-time convergence and obstacle/collision avoidance. In contrast with the multiagent formation reconfiguration²⁸ and multi-UAV formation reconfiguration without obstacle/collision avoidance,²⁹ we mainly focus on the neural network-based reconfiguration algorithm (NNRA) design for SFR with finite-time obstacle/collision avoidance. Comparing with the highly conservative finite-time coordination algorithm,³² which required the linearization and the boundedness constraints of the system, we propose an effective strategy with less conservatism and computational load by employing a novel adaptive neural network control technique. In contrast with the finite-time fault-tolerant control for a 6-degree-of-freedom spacecraft,³³ we investigate the problem of SFR for multiple spacecraft. Comparing with the finite-time consensus algorithms for multiagent systems,^{34,35} we commit to construct a finite-time formation reconfiguration algorithm for a multiple spacecraft system with obstacle/collision avoidances.

Up to now, no solution to the SFR control problem with less conservatism and computational load, finite-time convergence, and collision/obstacle avoidance has been well presented. The highlight of this paper is to design an NNRA for the finite-time coordination tracking of SFR in obstacle environments with less conservatism and computational load, and the design philosophy is inspired by the idea of compound control.³⁶ The main contributions are stated as follows.

1. A novel NNRA with only 1 adaptive parameter is presented for SFR in obstacle environments. It can guarantee all the spacecraft to form a desired rigid formation in finite time with less conservatism and lower computational load.
2. The proposed algorithm can achieve rapidity, accuracy, disturbance attenuation, and obstacle/collision avoidance capability. Moreover, no prior information of the inhibit modeling uncertainties and external disturbances is required.
3. No a priori knowledge of the desired trajectory is required in the NNRA. The predesigned desired trajectory is calculated online by adopting null space-based behavioral control (NSB) associated with the finite-time control theory.

The rest of the paper is organized as follows. Section 2 describes the control problem and provides preliminaries. The controller design and stability analysis for SFR are formulated in Section 3. Section 4 gives the simulation examples to demonstrate the effectiveness and performance of the proposed solution. Finally, the conclusions are provided in Section 5.

*See other works,^{2-4,6,8,11,15-19}

†See other works,^{5,7,9,10,12-14,20}

2 | PRELIMINARIES

2.1 | Spacecraft dynamics

A group of spacecraft containing n followers and 1 leader is considered in this paper, where the dynamics of the i th follower is modeled as¹⁹

$$m_{f,i}\ddot{p}_i + C_{t,i}(\omega_{i,l}^l)\dot{p}_i + D_{t,i}(\dot{\omega}_{i,l}^l, \omega_{i,l}^l, r_{f,i})p_i + n_{t,i}(r_l, r_{f,i}) = F_{a,i} + F_{d,i} \quad (1)$$

for $i = 1, \dots, n$, where $r_l \in \mathbb{R}$ and $r_{f,i} \in \mathbb{R}$ represent the distance from the center of Earth to the leader in $\mathcal{F}^l$ and the follower in $\mathcal{F}^{f,i}$, respectively.

Remark 1. Suppose that the leader is perfectly controlled in its orbit; thus, $f_{al} = -f_{dl}$, $F_{a,i} = f_{af,i}$, and $F_{d,i} = f_{df,i}$ hold. Furthermore, if $R_l^i p_i = -r_l$, the follower will be situated at the center of the orbit, which will lead to singularity in Equation (1), but this conclusion only pertains in $\mathbb{R}^n$.

Remark 2. $m_{f,i}$ is assumed to be uncertain due to fuel consumption; thus, it cannot be used in the control design directly. Suppose that the rate of fuel consumption is $\Delta m_{f,i} \in [\Delta \bar{m}_{f,i}, \Delta \underline{m}_{f,i}]$, then $m_{f,i}$ and $\dot{m}_{f,i}$ can be expressed as $m_{f,i} = \bar{m}_{f,i} - \Delta m_{f,i}t$ and $\dot{m}_{f,i} = -\Delta m_{f,i}$, where $\Delta \bar{m}_{f,i} > 0$ and $\Delta \underline{m}_{f,i} \geq 0$ are the maximum and minimum rates of fuel consumption and $\bar{m}_{f,i}$ is the initial mass of the i th follower.

2.2 | Concepts of obstacle avoidance and collision avoidance

Obstacle avoidance means keeping an allowable distance between a spacecraft and an obstacle. Collision avoidance is defined as avoiding collisions between spacecraft. Figure 1A shows the sectional drawing of the obstacle region $B_{i,o}$ of spacecraft i . When an obstacle is entering $B_{i,o}$, the obstacle avoidance task is activated by the supervisor. The spacecraft, which is out of control or entering the others' virtual sphere, is treated as an obstacle. Figure 1B shows the sectional drawing of the collision region $B_{i,o}$ of spacecraft i . Once spacecraft k is entering $B_{i,o}$, the collision avoidance task is activated by the supervisor. For definiteness and without loss of generality, the collision avoidance task is also called the obstacle avoidance task in the following analysis. In particular, if multiple obstacles appear around the spacecraft, the nearest one will be treated in priority.

2.3 | Control objective

By utilizing the universal approximation ability of NN, we aim to design an NNRA such that each follower spacecraft can be reconfigured to the desired position by tracking the predesigned trajectory $p_d(t)$ and velocity signal $\dot{p}_d(t)$, while the obstacle avoidance subtask (OAS) and the formation subtask perform in finite time. Meanwhile, all the spacecraft can

FIGURE 1 Sectional drawing of the obstacle/collision region $B_{i,o}$ for the i th spacecraft. A, Sectional drawing of the obstacle region; B, Sectional drawing of the collision region [Colour figure can be viewed at wileyonlinelibrary.com]

reconfigure and maintain a fixed formation while meeting the control requirements of fast response, high precision, and strong robustness.

2.4 | Assumptions and lemmas

Assumption 1. The mass $m_{f,i}$ is bounded, ie, $\|m_{f,i}\| \leq \varsigma_{1i}$ with $\varsigma_{1i} > 0$ as an unknown constant.

Assumption 2. The CPF $F_{d,i}$ is bounded such that $\|F_{d,i}\| \leq \varsigma_{2i}$, where $\varsigma_{2i} > 0$ is an unknown constant.

Assumption 3. The nonlinear function $g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) = -[m_{f,i}\ddot{p}_{r,i} + C_{t,i}(\omega_{i,l}^l)\dot{p}_{r,i} + D_{t,i}(\dot{\omega}_{i,l}^l, \omega_{i,l}^l, r_{f,i})p_i + n_{t,i}(r_l, r_{f,i})]$ is bounded with

$$\begin{aligned} \|g_i\| &\leq \theta_{1,i} \left(\|\ddot{p}_{r,i}\| + 2 \|\omega_{i,l}^l \dot{p}_{r,i}\| + \left\| \left(S^2(\omega_{i,l}^l) + S(\dot{\omega}_{i,l}^l) + I_3 \mu / r_{f,i}^3 \right) p_i \right\| + \mu \left\| R_i^l \left[1/r_{f,i}^3 - 1/r_l^3 \right] r_l \right\| \right) + \theta_{2,i} \\ &= \theta_i^T \varphi_i, \end{aligned} \quad (2)$$

where $\ddot{p}_{r,i}$ and $\dot{p}_{r,i}$ are specified in (8). $\theta_i = [\theta_{1,i}, \theta_{2,i}]^T$ with $\theta_{1,i} > 0$, $\theta_{2,i} > 0$, and $\varphi_i = [\varphi_{1,i}, \varphi_{2,i}]^T$ with $\varphi_{1,i} = \|\ddot{p}_{r,i}\| + 2\|\omega_{i,l}^l \dot{p}_{r,i}\| + \|(S^2(\omega_{i,l}^l) + S(\dot{\omega}_{i,l}^l) + I_3 \mu / r_{f,i}^3)p_i\| + \mu\|R_i^l[1/r_{f,i}^3 - 1/r_l^3]r_l\|$, $\varphi_{2,i} = 1$.

Assumption 4. There exists an unknown constant $\bar{\delta}_i$ such that $\|F_{d,i} + \delta_i\| \leq \bar{\delta}_{i0}$, for $i = 1, \dots, n$, where δ_i is the approximation error.

Lemma 1. (See the work of Huang et al³⁷)

$\forall c > 0$, the inequality $a^n b^m \leq ca^{n+m} + \frac{m}{n+m} \left[\frac{n}{c(n+m)} \right]^{\frac{n}{m}} b^{n+m}$ holds for real numbers $n > 0$, $m > 0$, $a \geq 0$, and $b \geq 0$.

Lemma 2. (See the work of Hardy et al³⁸)

$\forall x_i \in \mathbb{R}$, $a \in (0, 1)$, for $i = 1, \dots, n$, it has $\left(\sum_{i=1}^n |x_i| \right)^a \leq \sum_{i=1}^n |x_i|^a$.

Lemma 3. (See the work of Yu et al³⁹)

An extended Lyapunov description of the finite-time stability can be given in the form of the fast terminal sliding mode as $\dot{V}(x) + \mu_1 V(x) + \mu_2 V^\nu(x) \leq 0$, and the settling time can be calculated by

$$T_{reach} \leq \frac{1}{\mu_1(1-\nu)} \ln \frac{\mu_1 V^{1-\nu}(x_0) + \mu_2}{\mu_2},$$

where $\mu_1 > 0$, $\mu_2 > 0$, $0 < \nu < 1$, and the initial value of $V(x)$ is $V(x_0)$.

3 | CONTROL DESIGN FOR THE FORMATION RECONFIGURATION

In this section, we discuss the control design methodology to solve the SFR control problem. The obstacle/collision avoidance problem is the key issue, and some traditional coordination/consensus methods, which only work under the ideal situation (without the capacity of obstacle/collision avoidance), are unable to reuse or be easily extended. An NNRA is presented, which satisfies the property of NSB kinematic acting (velocity error dominates position error). The finite-time convergence of the system errors can be achieved by the proposed strategy in 2 steps.

3.1 | Step 1: design of the desired velocity and trajectory for each spacecraft

In the first step, by utilizing NSB method together with finite-time control theory, a group of predesigned desired velocities $\dot{p}_{di}(t)$ and trajectories $p_{di}(t)$, for $i = 1, \dots, n$, are calculated to fulfill the formation reconfiguration task (FRT) with collision/obstacle avoidance.

The FRT is decomposed into 2 subtasks, which are the OAS $\mathcal{T}_o$ and formation subtask $\mathcal{T}_f$. The definitions of the 2 subtasks are elaborated as follows.

Obstacle avoidance subtask (OAS). The OAS function of the i th spacecraft is defined as $\mathcal{T}_{i,o} = \|p_i - p_i^o\|$, where p_i^o denotes the obstacle's generalized position of the i th spacecraft. Let d_i be the safe distance from the i th spacecraft to any obstacle or other spacecraft, and $\mathcal{B}_{i,o} = \{p_i, p_i^o \in \mathbb{R}^3 : \|p_i - p_i^o\| \leq d_i\}$ marks a sphere $\mathcal{T}_{i,od} = d_i$ for each spacecraft. Before calculating the trajectory, we design a novel desired velocity $\dot{p}_o(t) = [\dot{p}_{i,o}^T(t)]^T$ by employing the finite-time control and NSB method, ie,

$$\dot{p}_{i,o}(t) = \mathcal{J}_{i,o}^\dagger \Upsilon_{i,o} (\tilde{\mathcal{T}}_{i,o} + \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o})) \quad (3)$$

for $i = 1, \dots, n$, where $\mathcal{J}_{i,o}^\dagger = \mathcal{J}_{i,o}^T$, $\mathcal{J}_{i,o} = \hat{r}_i^T$, $\hat{r}_i = (p_i - p_i^o) / \|p_i - p_i^o\|$ represents a unity vector pointing at the current obstacle. The gain matrix $\Upsilon_{i,o} = \eta_{i,o}(\tilde{\mathcal{T}}_{i,o}, \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}), \|\dot{p}_i\|, \|\tilde{p}_i\|, \|\alpha_i(\tilde{p}_i)\|) I_3 > 0$, $\eta_{i,o}(\tilde{\mathcal{T}}_{i,o}, \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}), \|\dot{p}_i\|, \|\tilde{p}_i\|, \|\alpha_i(\tilde{p}_i)\|)$ is state-dependent as specified in (6). $\tilde{\mathcal{T}}_{i,o} = \mathcal{T}_{i,od} - \mathcal{T}_{i,o}$, and $\alpha_{i,o}(\tilde{\mathcal{T}}_{i,o})$ are a continuous switching function defined in notations. We define $\tilde{\mathcal{T}}_{i,o} > 0$ when the subtask is active and $\tilde{\mathcal{T}}_{i,o} = 0$ when the subtask is inactive.

The desired trajectory $p_o(t) = [p_{i,o}^T(t)]^T$ of OAS can be calculated by integrating $\dot{p}_o(t)$, and $\ddot{p}_o(t) = [\ddot{p}_{i,o}^T(t)]^T$ is defined likewise. $p_o(t)$, $\dot{p}_o(t)$, and $\ddot{p}_o$ are all bounded functions.

Formation subtask. Define the formation subtask function as $\mathcal{T}_f = [(p_i - p_b)^T]^T$, where $p_b = 1/n \sum_{i=1}^n p_i$ is the coordinate of the barycenter. Similar to Equation (3), we design the desired velocity $\dot{p}_f$ for the formation subtask as

$$\dot{p}_f = \mathcal{J}_f^\dagger \Lambda_f (\tilde{\mathcal{T}}_f + \alpha_f(\tilde{\mathcal{T}}_f)), \quad (4)$$

where $\Lambda_f = \eta_f I_{3n \times 3n} > 0$ is the matrix of gains, and the Jacobian matrix $\mathcal{J}_f = \text{block diag}\{\Gamma, \Gamma, \Gamma\} \in \mathbb{R}^{3n \times 3n}$ is given by

$$\Gamma = \begin{bmatrix} 1 - \frac{1}{n} & -\frac{1}{n} & \cdots & -\frac{1}{n} \\ -\frac{1}{n} & 1 - \frac{1}{n} & \cdots & -\frac{1}{n} \\ \vdots & \vdots & \ddots & \vdots \\ -\frac{1}{n} & -\frac{1}{n} & \cdots & 1 - \frac{1}{n} \end{bmatrix} \in \mathbb{R}^{n \times n}.$$

Γ has one zero eigenvalue and $(n - 1)$ one eigenvalue, which indicates $\text{rank}(\mathcal{J}_f) = 2n$, and $\mathcal{J}_f^\dagger = \mathcal{J}_f$. $\tilde{\mathcal{T}}_f = \mathcal{T}_{f,d} - \mathcal{T}_f$, where $\mathcal{T}_{f,d}$ is the spacecraft position in the desired formation. With a fixed desired formation $\mathcal{T}_{f,d}$, one has $\dot{\mathcal{T}}_{f,d} = 0$.

The desired trajectory $p_f(t) = [p_{i,f}^T(t)]^T$ for the formation subtask can be calculated by integrating $\dot{p}_f(t)$, and $\ddot{p}_f(t) = [\ddot{p}_{i,f}^T(t)]^T$ is defined likewise. $p_f(t)$, $\dot{p}_f(t)$, and $\ddot{p}_f(t)$ are all bounded functions.

Formation reconfiguration task (FRT). If the aforementioned 2 subtasks are completed, it means that the FRT is performed successfully. In the following analysis, we give OAS a higher priority, which means that it takes precedence when a conflict between the OAS and formation subtask occurs. By merging the 2 subtasks, the final desired trajectory $p_d(t) = [p_{di}^T(t)]^T$ can be deduced by integrating the merged desired velocity $\dot{p}_d(t) = [\dot{p}_{di}^T(t)]^T$ in (5), which is achieved by projecting $\dot{p}_{i,f}(t)$ onto the null space of vector $\dot{p}_{i,o}$, ie,

$$\dot{p}_{di}(t) = \dot{p}_{i,o} + \left(I_3 - \mathcal{J}_{i,o}^\dagger \mathcal{J}_{i,o} \right) \dot{p}_{i,f}. \quad (5)$$

Analogously, we can calculate $\ddot{p}_d(t) = [\ddot{p}_{di}^T(t)]^T$ by differentiating $\dot{p}_d(t)$. All the desired signals $p_d(t)$, $\dot{p}_d(t)$, and $\ddot{p}_d(t)$ are bounded.

Theorem 1. Capitalizing on Equation (5) for FRT, it has the following conditions:

1. If the OAS and formation subtask are conflicting, then the OAS is prioritized and accomplished preferentially, and $\tilde{\mathcal{T}}_{i,o}$ converges to $|\tilde{\mathcal{T}}_{i,o}| \leq \varsigma$ in finite time.
2. If the OAS and formation subtask are collision-free, then $\tilde{\mathcal{T}}_{i,o}$ and $\tilde{\mathcal{T}}_{i,f}$ converge to $|\tilde{\mathcal{T}}_{i,o}| \leq \varsigma$ and $\|\tilde{\mathcal{T}}_{i,f}\| \leq \varsigma$ in finite time, respectively.

Proof. See the proof of theorem 1 in the work of Zhou et al.³² □

Remark 3. The following constraint Equation (6) must be fulfilled for the reason that $\dot{\tilde{p}}_i$ should master $\tilde{p}_i$ according to the kinematics characteristics of NSB method (ie, a kinematic acting on the dynamics through the desired velocity and not the desired position), ie,

$$\eta_{i,o}(\tilde{\mathcal{T}}_{i,o}, \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}), \|\dot{p}_i\|, \|\tilde{p}_i\|, \|\alpha_i(\tilde{p}_i)\|) = \eta_{i,o}^*(\tilde{\mathcal{T}}_{i,o}, \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}), \|\dot{p}_i\|, \|\tilde{p}_i\|, \|\alpha_i(\tilde{p}_i)\|) + \bar{\eta}_{4i}, \quad (6)$$

where $\eta_{i,o}^* > 0$ is the minimum value of $\eta_{i,o}$ and is calculated by

$$\eta_{i,o}^* (\tilde{\mathcal{T}}_{i,o}, \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}), \|\dot{p}_i\|, \|\tilde{p}_i\|, \|\alpha_i(\tilde{p}_i)\|) = \frac{1}{2\bar{\eta}_{1i}} \left(-\bar{\eta}_{2i} + \sqrt{\bar{\eta}_{2i}^2 + 4\bar{\eta}_{1i}\bar{\eta}_{3i}} \right), \quad (7)$$

where $\bar{\eta}_{4i} > 0$ is a robust item utilized to reject, eg, measurement noise, $\bar{\eta}_{1i} = (\tilde{\mathcal{T}}_{i,o} + \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}))^2$, $\bar{\eta}_{2i} = -2(\tilde{\mathcal{T}}_{i,o} + \alpha_{i,o}(\tilde{\mathcal{T}}_{i,o}))(\|\dot{p}_i\| + c_1\|\tilde{p}_i\| + c_2\|\alpha_i(\tilde{p}_i)\|)$, $\bar{\eta}_{3i} = -\|\dot{p}_i\|^2 + c_1^2\|\tilde{p}_i\|^2 + c_2^2\|\alpha_i(\tilde{p}_i)\|^2 + 2c_1\|\dot{p}_i\|\|\tilde{p}_i\| + 2c_2\|\dot{p}_i\|\|\alpha_i(\tilde{p}_i)\|$ for $i = 1, \dots, n$, and c_1 and c_2 are 2 positive design parameters.

Remark 4. From the conclusions of Theorem 1, it shows that the predesigned desired trajectory can guarantee the finite-time convergence of OAS error $\tilde{\mathcal{T}}_{i,o}$, which means that $\|p_i - p_i^o\| \rightarrow d_i$ achieves in finite time.

3.2 | Step 2: control law design and stability analysis

In the second step, we aim to design a neural network-based coordination controller (NNCC) $f_{af,i}$ for $i = 1, \dots, n$, which can ensure each spacecraft to track its merged predesigned desired trajectory $p_{di}(t)$ while achieving the required response rate, precision, and robustness control qualifications.

Before the further design and analysis, we first define a reference trajectory p_r and construct a variable structure ϵ as follows:

$$\epsilon = \dot{p} - \dot{p}_r, \quad (8)$$

where $\epsilon = [\epsilon_i^T]^T$, $\epsilon_i = [\epsilon_{i,j}]^T$, $p_r = [p_{r,i}^T]^T = [(p_{di} - c_1\tilde{p}_i - c_2\alpha_i(\tilde{p}_i))^T]^T$ is required only for analytical purposes, and $\dot{p}_r = [\dot{p}_{r,i}^T]^T = [(\dot{p}_{di} - c_1\dot{\tilde{p}}_i - c_2\dot{\alpha}_i(\tilde{p}_i))^T]^T$, $\tilde{p} = [\tilde{p}_i^T]^T = [(p_i - p_{di})^T]^T$, and $\alpha(\tilde{p}) = [\alpha_i(\tilde{p}_i)^T]^T$, for $j = 1, 2, 3$.

By inserting Equation (8) into Equation (1), the dynamics can be rewritten as

$$m_{f,i}\dot{\epsilon}_i + C_{t,i}(\omega_{i,l}^l)\epsilon_i = F_{a,i} + F_{d,i} + g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i), \quad (9)$$

where

$$g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) = -m_{f,i}\ddot{p}_{r,i} - C_{t,i}(\omega_{i,l}^l)\dot{p}_{r,i} - D_{t,i}(\omega_{i,l}^l, \omega_{i,l}^l, r_{f,i})p_i - n_{t,i}(r_l, r_{f,i}). \quad (10)$$

Equation (10) is an unknown nonlinear function, which is bounded according to Assumption 3.

3.2.1 | NN-based approximation theory

In the following design process, NN is utilized to eliminate the adverse effect from the unknown nonlinear function $g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i)$. By using the universal approximation ability of NN,⁴⁰ we can approximate a continuous nonlinear function $f(z): \mathbb{R}^l \rightarrow \mathbb{R}^m$ on a compact set as follows:

$$f_{NN}(W, z) = W^T \phi(z),$$

where $W \in \mathbb{R}^{q \times m}$ signifies an adjustable weight matrix. $z \in \Omega_z \subset \mathbb{R}^l$, Ω_z is a compact set; $\phi(z) = [\phi_1(z), \dots, \phi_q(z)]^T$ represents a basis function vector, which can be chosen as sigmoids, Gaussians, etc; and q is the neuron's number.

Taking $f(z) \in \mathbb{R}^m$ as an example, it can be approximated as accurately as possible by using the ideal weights matrix W^* on $\Omega_z \subset \mathbb{R}^l$, ie,

$$f(z) = W^{*T} \phi(z) + \delta_z,$$

where $W^* \in \mathbb{R}^{q \times m}$ signifies the NN's optimal weight matrix. In general, W^* is only used for analysis purposes, which needs to be estimated. The minimum possible deviation between $W^{*T} \phi(z)$ and $f(z)$ is represented as $\delta_z \in \mathbb{R}^m$, which is bounded with $\|\delta_z\| \leq \delta_N$, where δ_N is a positive constant.

For all $z \in \Omega_z \subset \mathbb{R}^l$, W^* is given by

$$W^* \triangleq \operatorname{argmin}_{W \in \mathbb{R}^{q \times m}} \left\{ \sup_{z \in \Omega_z} \|f(z) - W^T \phi(z)\| \right\}.$$

Remark 5. It should be noted that by increasing q , the NN approximation error δ_z can be reduced to the desired smallness. Furthermore, from the number of practical applications of NNs, it shows that $\|\delta_z\|$ can be made arbitrarily small if q is large enough.

3.2.2 | Main results

By employing NN, one can approximate the nonlinear function $g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i)$ to arbitrary precision as

$$g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) = W_i^{*T} \phi_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) + \delta_i, \quad (11)$$

where $W_i^* = [W_{i,1}^*, W_{i,2}^*, W_{i,3}^*] \in \mathbb{R}^{q_i \times 3}$ is the NN optimal weight matrix and W_i^* is written as $W_{i,j}^* = [W_{i,j}^{1*}, \dots, W_{i,j}^{q_i*}]^T \in \mathbb{R}^{q_i}$ for $j = 1, 2, 3$. $\delta_i \in \mathbb{R}^3$ is the approximation error, and $\phi_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) = [\phi_{i,1}, \dots, \phi_{i,q_i}]^T \in \mathbb{R}^{q_i}$ is the basis function vector.

For the further design, we define a new parameter $\bar{W}_i = \max_i \{ \max_j \{ \max_k \{ (W_{i,j}^{k*})^2 \} \}, \bar{\delta}_{i0}^2 \}$, and the function $\Phi_i = \sum_{j=1}^{q_i} \phi_{i,j}^2 + 1$. Let $\hat{W}_i$ be the estimation of $\bar{W}_i$, and $\tilde{W}_i = \bar{W}_i - \hat{W}_i$ be the estimation error.

The NNCC is derived as

$$f_{af,i} = - \left(v_{1i} + \frac{1}{2\zeta^0} \hat{W}_i \Phi_i \right) \epsilon_i - v_{2i} \epsilon_i^{\frac{1}{2}} \quad (12)$$

with the adaptation law

$$\dot{\hat{W}}_i = \frac{\gamma_{1i}}{2\zeta^0} \Phi_i \|\epsilon_i\|^2 - \gamma_{2i} \hat{W}_i - \frac{\gamma_{2i}}{4} \text{sgn}(\hat{W}_i), \quad (13)$$

where v_{1i} , v_{2i} , γ_{1i} , and γ_{2i} are positive design parameters and ζ^0 satisfies $0 < \zeta^0(t) \leq \zeta_m^0$ with $\zeta_m^0 > 0$.

Now, the analysis results are presented as follows.

Theorem 2. For system (1), if the constraint (6) and Assumptions 1 to 4 are satisfied and the NNRA is provided by (12) and (13), then the FRT is achieved, and system errors $\tilde{p}_{i,j}$, $\dot{\tilde{p}}_{i,j}$ converge to $|\tilde{p}_{i,j}| \leq \bar{\delta}_{13}$, $|\dot{\tilde{p}}_{i,j}| \leq \bar{\delta}_{14}$, respectively, in finite time with $\bar{\delta}_1 = \min \{ \bar{\delta}_{11}, \bar{\delta}_{12} \}$, $\bar{\delta}_{11} = \sqrt{\frac{2\eta_{13}}{\eta_{11} \min_i \{ m_{f,i} \}}}$, $\bar{\delta}_{12} = \sqrt{\frac{1}{\min_i \{ m_{f,i} \}} (\frac{2\eta_{13}}{\eta_{12}})^{\frac{4}{3}}}$, $\bar{\delta}_{13} = \max \{ \zeta, \min \{ \bar{\delta}_1/c_1, (\bar{\delta}_1/c_2)^2 \} \}$, and $\bar{\delta}_{14} = \bar{\delta}_1 + c_1 \bar{\delta}_{13} + c_2 \sqrt{\bar{\delta}_{13}}$.

Proof. Choose the suitable Lyapunov candidate function as

$$V(t) = \frac{1}{2} \epsilon^T m_f \epsilon + \sum_{i=1}^n \frac{1}{2\gamma_{1i}} \tilde{W}_i^2, \quad (14)$$

where $m_f = \text{diag}\{m_{f,1}, \dots, m_{f,n}\} \otimes I_3$. Taking the time derivative of $V(t)$ along Equation (9) gives that

$$\begin{aligned} \dot{V}(t) &= \epsilon^T m_f \dot{\epsilon} + \frac{1}{2} \dot{m}_f \epsilon^T \epsilon - \sum_{i=1}^n \frac{1}{\gamma_{1i}} \tilde{W}_i \dot{\tilde{W}}_i \\ &= \sum_{i=1}^n \epsilon_i^T \left[F_{a,i} + F_{d,i} + g_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) - C_{t,i} \left(\omega_{i,l}^l \right) \epsilon_i \right] + \frac{1}{2} \dot{m}_f \epsilon^T \epsilon - \sum_{i=1}^n \frac{1}{\gamma_{1i}} \tilde{W}_i \dot{\tilde{W}}_i \\ &\leq \sum_{i=1}^n \epsilon_i^T \left[F_{a,i} + W_i^{*T}(t) \phi_i(\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i) + F_{d,i} + \delta_i - C_{t,i} \left(\omega_{i,l}^l \right) \epsilon_i \right] - \frac{1}{2} \Delta m_f \epsilon^T \epsilon - \sum_{i=1}^n \frac{1}{\gamma_{1i}} \tilde{W}_i \dot{\tilde{W}}_i, \end{aligned} \quad (15)$$

where $\dot{m}_f = \text{diag}\{-\Delta m_{f,1}, \dots, -\Delta m_{f,n}\} \otimes I_3$ and $\Delta m_f = \min_i \{ \Delta m_{f,i} \}$ for $i = 1, \dots, n$. Utilizing the skew-symmetric property of $C_{t,i}(\omega_{i,l}^l)$ and Assumption 4 and substituting Equations (12) and (13) into Equation (15), one obtains

$$\begin{aligned} \dot{V}(t) &\leq \sum_{i=1}^n \epsilon_i^T \left[- \left(v_{1i} + \frac{1}{2\zeta^0} \hat{W}_i \Phi_i \right) \epsilon_i - v_{2i} \epsilon_i^{\frac{1}{2}} \right] - \frac{1}{2} \Delta m_f \epsilon^T \epsilon + \frac{1}{2\zeta^0} \sum_{i=1}^n \tilde{W}_i \Phi_i \|\epsilon_i\|^2 \\ &\quad + \bar{\zeta} - \sum_{i=1}^n \frac{1}{2\zeta^0} \tilde{W}_i \Phi_i \|\epsilon_i\|^2 + \sum_{i=1}^n \frac{\gamma_{2i}}{\gamma_{1i}} \tilde{W}_i \hat{W}_i + \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} \tilde{W}_i \text{sgn}(\hat{W}_i) \\ &\leq \sum_{i=1}^n \left[- \left(v_{1i} + \frac{1}{2} \Delta m_{f,i} \right) \epsilon_i^T \epsilon_i - v_{2i} \epsilon_i^T \epsilon_i^{\frac{1}{2}} \right] + \sum_{i=1}^n \frac{\gamma_{2i}}{\gamma_{1i}} \tilde{W}_i \hat{W}_i + \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} \tilde{W}_i \text{sgn}(\hat{W}_i) + \bar{\zeta}, \end{aligned} \quad (16)$$

where $\bar{\zeta} = n\zeta^0/2$. Before continuing, Equation (17) is acquired by utilizing Lemma 1, ie,

$$\frac{\gamma_{2i}}{\gamma_{1i}} \tilde{W}_i \hat{W}_i \leq - \frac{\gamma_{2i}}{2\gamma_{1i}} \tilde{W}_i^2 + \frac{\gamma_{2i}}{2\gamma_{1i}} \bar{W}_i^2. \quad (17)$$

Adding and subtracting $\sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} |\tilde{W}_i|^{\frac{3}{2}}$ to the right side of Equation (16) and substituting Equation (17) into Equation (16), one has

$$\begin{aligned} \dot{V}(t) &\leq \sum_{i=1}^n \left[-\left(v_{1i} + \frac{1}{2} \triangle m_{f,i}\right) \epsilon_i^T \epsilon_i - v_{2i} \epsilon_i^T \epsilon_i^{\frac{1}{2}} \right] - \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} \tilde{W}_i^2 + \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} \bar{W}_i^2 \\ &\quad + \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} \bar{W}_i - \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} |\hat{W}_i| + \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} |\tilde{W}_i|^{\frac{3}{2}} - \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} |\tilde{W}_i|^{\frac{3}{2}} + \bar{\zeta} \\ &\leq \sum_{i=1}^n \left[-\left(v_{1i} + \frac{1}{2} \triangle m_{f,i}\right) \epsilon_i^T \epsilon_i - v_{2i} \epsilon_i^T \epsilon_i^{\frac{1}{2}} \right] - \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} \tilde{W}_i^2 - \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} |\tilde{W}_i|^{\frac{3}{2}} \\ &\quad - \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} \left[|\tilde{W}_i| - |\tilde{W}_i|^{\frac{1}{2}} \right]^2 + \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} \bar{W}_i + \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} \bar{W}_i^2 + \bar{\zeta} \\ &\leq \sum_{i=1}^n \left[-\left(v_{1i} + \frac{1}{2} \triangle m_{f,i}\right) \epsilon_i^T \epsilon_i - v_{2i} \epsilon_i^T \epsilon_i^{\frac{1}{2}} \right] - \sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} \tilde{W}_i^2 - \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} |\tilde{W}_i|^{\frac{3}{2}} + \eta_{13}. \end{aligned} \quad (18)$$

With the aid of Lemmas 2 and 3, one obtains

$$\dot{V}(t) + \eta_{11} V + \eta_{12} V^{\frac{3}{4}} \leq 0 \quad (19)$$

for $\sqrt{V(t)} \geq \eta_{14}$, where $\eta_{11} = \min_i \left\{ \frac{2v_{1i} + \triangle m_{f,i}}{m_{f,i}}, \frac{\gamma_{2i}}{2} \right\}$, $\eta_{12} = \min_i \left\{ v_{2i} \left(\frac{2}{m_{f,i}} \right)^{\frac{3}{4}}, \gamma_{2i} / (2\gamma_{1i})^{\frac{1}{4}} \right\}$, $\eta_{13} = \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} \bar{W}_i + \sum_{i=1}^n \frac{\gamma_{2i}}{2\gamma_{1i}} \bar{W}_i^2 + \bar{\zeta}$, and $\eta_{14} = \min \left\{ \sqrt{\eta_{13}/\eta_{11}}, \sqrt[3]{(\eta_{13}/\eta_{12})^2} \right\}$.

On the basis of the analysis process in the work of Zhou and Xia,³⁰ one calculates that $\sqrt{V(t)}$ converges to $\sqrt{V(t)} \leq \eta_{14}$ in finite time, which means that ϵ_i converges to the region $\|\epsilon_i\| \leq \bar{\delta}_1$ in finite time, where $\bar{\delta}_1 = \min \{ \bar{\delta}_{11}, \bar{\delta}_{12} \}$, $\bar{\delta}_{11} = \sqrt{\frac{2\eta_{13}}{\eta_{11} \min_i \{ m_{f,i} \}}}$, and $\bar{\delta}_{12} = \sqrt{\frac{1}{\min_i \{ m_{f,i} \}} \left(\frac{2\eta_{13}}{\eta_{12}} \right)^{\frac{4}{3}}}$. $\tilde{p}_{i,j}$ and $\dot{\tilde{p}}_{i,j}$ reach to $|\tilde{p}_{i,j}| \leq \bar{\delta}_{13}$ and $|\dot{\tilde{p}}_{i,j}| \leq \bar{\delta}_{14}$ in finite time, respectively, with $\bar{\delta}_{13} = \max \{ \zeta, \min \{ \bar{\delta}_1/c_1, (\bar{\delta}_1/c_2)^2 \} \}$ and $\bar{\delta}_{14} = \bar{\delta}_1 + c_1 \bar{\delta}_{13} + c_2 \sqrt{\bar{\delta}_{13}}$. These results derive that the i th spacecraft can move away from the obstacle if OAS is activated, and the FRT can be implemented subject to Assumptions 1 to 4 and the constraint Equation (6). $\square$

Remark 6. In summary, the proposed control algorithm can be driven by 6 steps:

1. Compute $\dot{p}_{di}(t)$ by utilizing (3)-(5);
2. Calculate $p_{di}(t)$ and $\ddot{p}_{di}(t)$ by integrating and differentiating $\dot{p}_{di}(t)$;
3. Calculate ϵ_i by the use of (8);
4. Calculate $\Phi_i = \sum_{j=1}^{q_i} \phi_{i,j}^2 + 1$;
5. Calculate $f_{af,i}$ by utilizing (12);
6. Update $\hat{W}_i(t)$ by the use of (13).

Remark 7. It is well known that both of the variable structure control and adaptive control have the merit of robustness against model uncertainties and external disturbances. In the proposed algorithm (12), the sliding-mode variable structure is denoted as ϵ_i , and the adaptive parameter $\hat{W}_i$ is the estimate of the artificial design parameter $\bar{W}_i$ extracted from the NN optimal weight matrix. In order to improve the robustness and weaken chattering phenomenon caused by ϵ_i , an NN reaching law is designed in the term $-\frac{1}{2\zeta^0} \hat{W}_i \Phi_i \epsilon_i$. Moreover, the term $-v_{2i} \epsilon_i^{\frac{1}{2}}$ is a power reaching law, which ensures that all the tracking errors reach to small regions in a finite time and low chattering is caused in the sliding motion. Meanwhile, the term $-\frac{\gamma_{2i}}{4} \text{sgn}(\hat{W}_i)$ in the adaptive law is used to construct the term $-\sum_{i=1}^n \frac{\gamma_{2i}}{4\gamma_{1i}} [|\tilde{W}_i| - |\tilde{W}_i|^{\frac{1}{2}}]^2$ in (18). In addition, simulation results can further verify the reliability and robustness of the proposed approach in Section 4.

Remark 8. The control objective enforces each spacecraft to track the predesigned trajectory $p_d(t)$ and velocity $\dot{p}_d(t)$. The reference trajectory p_r in (8) is required only for the analytical purposes. From lemma 3.1 in the work of Zhou et al.,²⁰ it is concluded that for any bounded $\tilde{p}_{i,j}(0)$ and $\dot{\tilde{p}}_{i,j}(0)$, if ϵ_i is bounded, then $\tilde{p}_{i,j}$ and $\dot{\tilde{p}}_{i,j}$ will be bounded

in finite time. Thus, the finite-time convergence of position error component $|\tilde{p}_{i,j}| \leq \bar{\delta}_{13}$ and velocity error component $|\dot{\tilde{p}}_{i,j}| \leq \bar{\delta}_{14}$ can be guaranteed from the finite-time convergence of $\|\epsilon_i\| \leq \bar{\delta}_1$.

Remark 9. Comparing with the works of Chen et al²⁵ and Zhou and Xia,⁴¹ the proposed control algorithm (12)-(13) is strong and robust against model uncertainty and nonlinearity, whereas the algorithms in the aforementioned works^{25,41} can only be applied to a linearizable nonlinear system. Furthermore, only 1 extracted adaptation parameter $\bar{W}_i$ is utilized in this paper in contrast with $q+1$ and q parameters for each agent in the works of Chen et al²⁵ and Zhou and Xia⁴¹, respectively, where q denotes the dimension of parameter. Thus, from the works of Ge et al⁴² and Liu and Tong,⁴³ it can be further concluded that the proposed control scheme can alleviate the computation burden because a few number of adaptive parameters are updated. Moreover, the proposed approach guarantees the finite-time convergence of the task errors and tracking errors, simultaneously, in contrast with the asymptotic convergence of the task errors in the works of Chen et al²⁵ and Zhou and Xia.⁴¹

4 | NUMERICAL SIMULATIONS

Two scenarios are provided in this section to testify the efficiency of the proposed NNRA. Six spacecraft with a well-controlled leader are taken into account,¹ in which the spacecraft are assumed to be running in a 600-km altitude circular low Earth orbit (LEO). The system model parameters and CPFs are chosen as in the work of Zhou and Xia.³⁰ The control force $f_{af,i,j}$ is confined to satisfy $|f_{af,i,j}| \leq 100$ N, and the acceleration $\ddot{p}_{i,j}$ is confined to meet $|\ddot{p}_{i,j}| \leq 1$ m/s² according to the nominal mass of spacecraft in Equation (1). Some other initial values of parameters are shown in Table 1, where $i = 1, \dots, 5, j = 1, 2, 3$. Radial basis function NN is adopted in the simulations, where $\hat{W}_i^0 \in \mathbb{R}^{60 \times 3}$ is the initial values of $\hat{W}_i$, and $q_i = 60$. Denote $z_i(t) = [\ddot{p}_{r,i}, \dot{p}_{r,i}, p_i]^T \in \Omega_z \subset \mathbb{R}^9$ as the input vector. The basis function vector is

TABLE 1 Numerical simulation parameters

d_i	η_f	$\bar{\eta}_{4i}$	v_{1i}	v_{2i}	c_1	c_2	r	ζ	γ_{1i}	γ_{2i}	ζ^0	q_i	$\hat{W}_{i,j}^0$
10	0.8	1	3	1	0.8	0.8	0.6	10^{-3}	0.8	0.8	0.5	60	$0^{60 \times 3}$

FIGURE 2 A, Relative distances $\|p_i - p_o\|$; B, Trajectories p_i and p_o for $i = 1, \dots, 5$ [Colour figure can be viewed at wileyonlinelibrary.com]

$\phi_i = [\phi_{i,k}]^T \in \mathbb{R}^{60}$ with $\phi_{i,k} = \exp[-(z_i - \bar{\mu}_{i,k})^T(z_i - \bar{\mu}_{i,k})/\zeta_k^2]$ for $k = 1, \dots, 60$, where $\bar{\mu}_{i,k} = [\bar{\mu}_{i,k,l}]^T$ is the receptive field's center for $l = 1, \dots, 9$, and evenly spaced in the range of $[-3, 3]^9$ and $\zeta_k = 2$ denotes the Gaussian function's width.

FIGURE 3 Plot 1: relative distance $\|p_2 - p_3\|$; Plot 2: the 2nd spacecraft's actuator force; Plot 3: the 3rd spacecraft's actuator force [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 4 Plot 1: relative distance $\|p_4 - p_5\|$; Plot 2: the 4th spacecraft's actuator force; Plot 3: the 5th spacecraft's actuator force [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 The trajectories of 5 followers, where the initial positions are marked by $\circ$, desired positions are marked by $\times$, and red solid $\bullet$ represents an obstacle [Colour figure can be viewed at wileyonlinelibrary.com]

Scenario 1: OAS

Suppose that there is a dynamic obstacle p_o , marked by a hollow circle $\bigcirc$, drifting through a rigid formation along a straight line with the initial position of $[-60, 8, 0]^T$ and the initial velocity of $[1, 0.6, 0]^T$. The formation is constituted by 5 spacecraft with $p_{init} = [(-50, 0, 0), (-25, 15, 0), (0, 30, 0), (25, 15, 0), (50, 0, 0)]^T$. In the simulation, 5 spacecraft are marked by $\triangleright, \triangleleft, *, \nabla$, and $\triangle$, respectively. It is obvious that the proposed NNRA is successfully applied to the smoother OAS execution in Figure 2, which shows that spacecraft 2 and 4 avoid the obstacle rapidly and precisely while holding a 10 m required distance. The demonstration in Figure 2 shows that the NNRA is efficient, and constraint Equation (6) is confirmed.

Scenario 2: Formation subtask with collision occurrence

As with table II in the work of Zhou and Xia,³⁰ we select the same individual initial and desired positions for spacecraft 1 to 5. The relative distance between spacecraft 2 and 3 is demonstrated in Plot 1 of Figure 3, and their actuator forces are given in Plots 2 and 3 of Figure 3. Apparently, after about 2 s, spacecraft 2 and 3 enter each others' safety spheres; therefore, the OAS is motivated with the actuator forces' switching. From Figure 3, it also shows that the relative distance between spacecraft 2 and 3 remains at 50 m after 8 s, and each component of actuator force is less than 100 N. Similar results on the fourth and fifth spacecraft are given in Figure 4, which shows that the relative distance between them reaches a security constant after 8 s, and the actuator forces satisfy the constraint condition. The corresponding trajectories of the 5 followers are given in Figure 5. The tracking errors $\|p_i - p_{di}\|$, for $i = 1, \dots, 5$, are shown in Figure 6A by using the proposed algorithm (12)-(13), which shows that the convergence accuracy can reach 2.5×10^{-4} m between 46.6 ~ 46.7 s. It demonstrates that NNRA can achieve the control objective while providing superior performance.

Scenario 3: Comparison

Some comparisons have been provided in Figures 6, 7, and 8 by using different controllers for SFR. Figures 6 to 8 show the results of the tracking errors $\|p_i - p_{di}\|$, the overall control effort $CPI_c = \sqrt{\sum_{i=1}^5 \|f_{af,i}\|^2}$, and the overall

FIGURE 6 Tracking error $\|p_i - p_{di}\|$. A, using the algorithm (12)-(13); B, using the algorithm proposed in the work of Zhou et al.³²; C, using the algorithm proposed in the work of Zhou and Xia,³⁰ and D, using the algorithm proposed in the work of Schlanbusch et al.¹ [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Response of the overall control effort CPI_c . A, using the algorithm (12)-(13); B, using the algorithm proposed in the work of Zhou et al,³²; C, using the algorithm proposed in the work of Zhou and Xia,³⁰ and D, using the algorithm proposed in the work of Schlanbusch et al¹

FIGURE 8 Response of the overall tracking accuracy CPI_e . A, using the algorithm (12)-(13); B, using the algorithm proposed in the work of Zhou et al,³²; C, using the algorithm proposed in the work of Zhou and Xia,³⁰ and D, using the algorithm proposed in the work of Schlanbusch et al¹

tracking accuracy $CPI_e = \sqrt{\sum_{i=1}^5 \|p_i - p_{di}\|^2}$ by using the proposed algorithm (12)-(13) and 3 previous algorithms from other works,^{1,30,32} respectively. As observed from Figures 6 and 8, we see that the proposed NNRA, which requires less conservatism, can provide much faster and more accurate response compared with existing approaches presented in other works,^{1,30,32} but larger control effort and slight control chattering is caused as shown in Figure 7.

5 | CONCLUSIONS

In the paper, the control problem of FRT has been investigated. The design philosophy is to construct an NNCC, which can ensure each spacecraft to track the predesigned velocity and trajectory. The predesigned desired trajectory is calculated by adopting the NSB method associated with finite-time control technology. To construct the NNRA, the adaptive NN-based strategy is employed to deal with the unknown nonlinear function of the error system. Meanwhile, the finite-time control theory is adopted to enhance the robustness and precision of the proposed algorithm. Based on Lyapunov's theory, the proposed NNRA stabilized the equilibrium point of the error system accordingly. Finally, simulation results illustrated that NNRA fulfills the FRT successfully. In future work, the extension of the presented control algorithm for formation problem as well as using only output measurements and estimated information can be planned. Another direction involves considering the control design problem of multiple control tasks (more than two tasks) for high-order multiagent systems.

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APPENDIX

The summarization of some important acronyms is listed in Table A1.

TABLE A1 Acronyms

Acronym	Meaning
NNRA	Neural network-based reconfiguration algorithm
NNCC	Neural network-based coordination controller
NSB	Null space-based behavioral control
FRT	Formation reconfiguration task
OAS	Obstacle avoidance subtask
CPF	Composite perturbation force
SFR	Spacecraft formation reconfiguration
SFF	Spacecraft formation flying