

Article

Robust Time-Varying Pinning Cooperative Control for Heterogeneous Air-Ground System with Switching Topologies and Uncertain Communication Links

Jianchao Zhang ¹, Zeng Zhao ² and Deyuan Liu ^{1,*}

¹ School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China; 16687075807@163.com

² Beijing Electro-Mechanical Engineering Institute, Beijing 100074, China; zhaozeng@buaa.edu.cn

* Correspondence: liudeyuan@buaa.edu.cn

Abstract

In this paper, a special air-ground system consisting of multiple tail-sitters and ground vehicles are constructed under switching topologies and uncertain communication links. For the air-ground system, the ground vehicles serve as the take-off and landing platforms for the tail-sitters. A robust time-varying pinning coordinated controller is developed for the heterogeneous system. The effects of parameter/link uncertainties and external disturbances are effectively attenuated via the devised control law. The robust performance of the air-ground cooperative control system with switching topologies is rigorously validated with the Lyapunov stability criterion. The steady-state tracking deviations satisfy uniform ultimate boundedness and converge within an infinitesimal region around the origin. Simulation tests are carried out to verify that the developed control scheme achieves satisfactory coordination under time-varying cases, with tracking deviations noticeably lower in comparison with conventional control schemes.

Keywords: air-ground cooperative control; heterogeneous system; robust pinning control; time-varying formation; switching topologies

1. Introduction

Over the past decades, multi-agent systems have garnered abundant research attention owing to their unique functional merits. A particular focus lies on the coordinated control schemes for heterogeneous multi-agent formation integrated with unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) [1–7]. UAVs are capable of high-velocity flight and broad observation coverage ranges, whereas UGV units possess superior long-duration operation and heavy-cargo carrying capacities. The hybrid UAV-UGV collaborative frameworks are capable of executing diverse sophisticated missions within dynamically unknown surroundings, including target detection and following, emergency rescue operations, and cargo transportation assignments. Furthermore, in traditional air-ground coordination systems, two classical configurations of UAVs are used, rotorcraft and fixed-wing aircraft. Fixed-wing platforms possess prominent merits including outstanding cruising economy and rapid flight velocity, whereas stable landing procedures remain practical difficulties. The rotorcraft have properties of taking off and landing vertically, but they need to consume more power to compensate for the effects of gravity. Recently, several tail-sitter UAVs have been developed because they can vertically fly as rotorcraft, while having the ability of high endurance as fixed-wing aircraft [8,9].



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However, developing collaborative control schemes for aerial-ground clusters poses considerable difficulties, due to the following reasons. First, there exist various heterogeneous characteristics (different workspace and dynamics) between tail-sitters and UGVs. The difference between the two models leads to the inconsistency of control target, which increases the difficulty of coordination controller design. Furthermore, in a cooperative mission, the operation terrain of a ground vehicle is complex, and tail-sitter has the characteristics of high flight speed and large airspace maneuvering flight. The controller of air-ground joint formation is required to respond quickly to form the time-varying formation, while communication channels always suffer from uncertain interferences. Besides, the heterogeneous collaborative framework contains inherent nonlinear characteristics, severe parametric uncertainties, and external environmental perturbations. Therefore, an effective cooperative control method is required for investigation.

Most existing studies about coordination control issues have mainly concentrated on groups of identical homogeneous platforms [10–12]. The collaborative control strategies for multi-type heterogeneous platform systems need further investigation, because each vehicle carries out different functional responsibilities in group cooperative operations. In [13,14], cooperative control frameworks were designed for quadrotor and ground robot clusters to complete object manipulation missions. In [15], a receding horizon reinforcement learning control approach was studied for multiple vehicles and ground vehicles. In [16], a robust controller was developed for heterogeneous robotic teams with multiple UAVs and UGVs. Ref. [17] constructed a joint coordination framework to adjust the monitoring positions of air-ground robots in the whole positioning procedure. In [18], a decentralized algorithm was presented for multiple vehicles to achieve collaboration scenarios. However, the external disturbances in the above mentioned controller design were not further considered.

In [19], the effects of air disturbances were discussed in the controller design for the heterogeneous robotic team consisting of UAVs and UGVs. A fixed-time trajectory tracking control algorithm was presented for air-ground hybrid robotic platforms under unknown external perturbations in [20] to realize stable formation control. Depending on leader-follower formation rules, an adaptive tracking control strategy was constructed for UAVs-UGVs system subjected to environmental effects [21]. However, the communication topology and coordination scenarios were unchanged in the aforementioned results [19–21]. Theoretical conclusions and control frameworks fail to guarantee formation stability under frequently changed information interaction relationships. The time-varying cooperative control scheme design for hybrid aerial-ground platforms subject to dynamically switching communication graphs requires comprehensive consideration.

On the other research front, the pinning control method is viewed as a feasible solution for cooperation control problems and has been widely used within multi-agent networks. In [22], an adaptive pinning consensus control architecture was constructed for heterogeneous vehicle group. To coordinate the flight of multiple helicopters, ref. [23] developed an anti-interference pinning control policy. In [24], a pinning-control-based state observer method was proposed for multi-robot groups to realize collective consensus behavior.

Moreover, the switching communication graphs were characterized as designable matrices in aforementioned works [2,16,25], and the information exchanges were ideal. In actual flight-ground movement, signal attenuation, transmission delay, and data loss will cause time-varying deviations in communication adjacency and pinning weights. The communication links are subject to uncertainties, which can seriously degrade the global control performance through network propagation. The problem of communication links with uncertainties needs to be further studied.

Motivated by the above analysis, this paper investigates time-varying cooperative control for a distinctive heterogeneous group of tail-sitter UAVs and UGVs under switching

topologies and uncertain communication links. A robust pinning cooperative control law is constructed for the mixed tail-sitter and UGV formation. In particular, a virtual leader is adopted as the pinning anchor, which directly controls partial air and ground vehicles (called pinned nodes). The rest of the vehicles connect to pinned nodes as adjacent nodes and gain indirect control to sustain the time-varying cooperative configuration. The contributions are three-fold as follows.

First, a distinctive heterogeneous air-ground collaborative group of multiple tail-sitter UAVs and UGVs is established under switching topologies and uncertain communication links. These tail-sitter platforms support vertical takeoff and landing operations on matched ground vehicles. This integrated cooperative architecture is capable of executing missions under unpredictable surroundings better than classical air-ground coordination frameworks. However, in [13,14,18], the UAV models were simplified, and thereby the corresponding formation control problems were simplified.

Second, a robust time-varying pinning coordination controller is developed for the heterogeneous system. A virtual leader is adopted as the pinning anchor, which directly controls partial air and ground vehicles (called pinned nodes). The rest of the vehicles connect to pinned nodes as adjacent nodes and gain indirect control to sustain the time-varying cooperative configuration. The proposed control scheme allows the multi-vehicle groups with switching topologies to implement dynamic formation missions within complicated conditions. But, the formation configurations discussed in [18–21] are static and independent of time variations.

Third, the ubiquitous disturbances and uncertainties acting on the air-ground coordination system are taken into consideration. A robust compensation method is proposed without requiring accurate prior modeling of lumped uncertainties. The established integrated air-ground cooperative controller is capable of guarantying strong anti-interference robustness. However, the compound effects generated by various uncertain factors were not discussed in [15–17].

The paper is arranged as follows. In Section 2, graph theory, nonlinear models of the heterogeneous system are described, and the problem statement is formulated. The constructed coordinated controller for the air-ground system and the proof of robustness are given in Sections 3 and 4, respectively. Section 5 gives simulation results on the coordination patterns of the special heterogeneous system. Section 6 concludes this paper.

2. Problem Formulation

This paper constructs a special air-ground system integrating tail-sitter aircraft and ground vehicles. The cooperation control problem for the heterogeneous vehicle group is considered. This section firstly introduces graph theory. Then, nonlinear dynamic mathematical descriptions of tail-sitter aircraft and ground platforms are derived, and the control task formulation is given.

2.1. Graph Theory

In the air-ground system, n tail-sitters and m ground vehicles are regarded as nodes represented by v_i . The information link between v_i and v_j is described by an edge (v_i, v_j) , and the two nodes are called adjacent. Define w_{ij} as the weight of (v_i, v_j) . Then, the information links of the air-ground coordination system can be specified as an interaction topology graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{W})$, where $\mathcal{V} = \{v_1, v_2, \dots, v_{n+m}\}$ denotes a node set, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ denotes an edge set, and $\mathcal{W} = [w_{ij}]$ denotes an adjacency matrix. If $(v_i, v_j) \in \mathcal{E}$, $w_{ij} = 1$; otherwise $w_{ij} = 0$. The neighbors of node v_i are involved in a set $N_{bi} = \{j | (v_i, v_j) \in \mathcal{E}\}$, if $w_{ij} = 1$, the node v_j can be regarded as a neighbor of v_i . Define the degree matrix as $\mathcal{D} = \text{diag}\{d_i\}$, where $d_i = \deg_{in}(v_i) = \sum_{j=1}^N w_{ij}$ represents the in-degree of node v_i . For

node i , the out-degree can be obtained by $\deg_{out}(v_i) = \sum_{j=1}^N w_{ji}$. Then, the Laplacian matrix L can be formulated by $L = \mathcal{D} - \mathcal{W}$. The link from node v_i to node v_j can be described as ordered edges $\{(v_i, v_p), (v_p, v_m), \dots, (v_n, v_j)\}$. In addition, a virtual leader is adopted as the pinning anchor, which directly controls partial air and ground vehicles (referred to as pinned nodes). The coupling gain connecting pinned node i and the virtual anchor is defined as d_{i0} . When agent i belongs to the pinned set, $d_{i0} > 0$, otherwise, $d_{i0} = 0$.

Furthermore, the switching topology in the heterogeneous air-ground system is considered. In practical application, the total mission time can be divided into a series of continuous bounded time intervals $[t_k, t_{k+1}) (k \in \Psi)$, where Ψ denotes a natural number set and $t_1 = 0$. For the time interval $[t_k, t_{k+1})$, the interaction topology switches at the time t_k and the dwell time t_Δ satisfies $0 < t_\Delta \leq t_{k+1} - t_k$. The interaction topology is unchanged in dwell time $[t_k, t_{k+1})$. Define switching signal representing the topology index at time t as $\sigma(t) : [0, +\infty) \rightarrow \mathcal{G}_n$, where $\mathcal{G}_n \in \Psi$ denotes a set of graph index. Then, one defines the topology graph as $\mathcal{G}_{\sigma(t)}$ at $\sigma(t)$, the link weight as $w_{\sigma(t)}^{ij}$, and the pinning weight as $d_{\sigma(t)}^{i0}$. The neighbor set of node v_i , the weight matrix, and the Laplacian matrix can be described as $N_{\sigma(t)}^{bi}$, $\mathcal{W}_{\sigma(t)}$, and $L_{\sigma(t)}$ at $\sigma(t)$, respectively.

2.2. Model of Air-Ground System

The framework of the air-ground cooperative platform is shown in Figure 1. In the cooperative system, the tail-sitter aircraft combines the characteristics of quadrotor and fixed-wing aircraft. The major thrust is produced by propellers mounted on tail-sitter head. The attitude under various flight operation modes is regulated by four rotors and two ailerons. For the air-ground system, a four-wheel independent drive ground mobile platform is adopted. The heading angle of the ground mobile platform can be conveniently adjusted through differential driving torques.

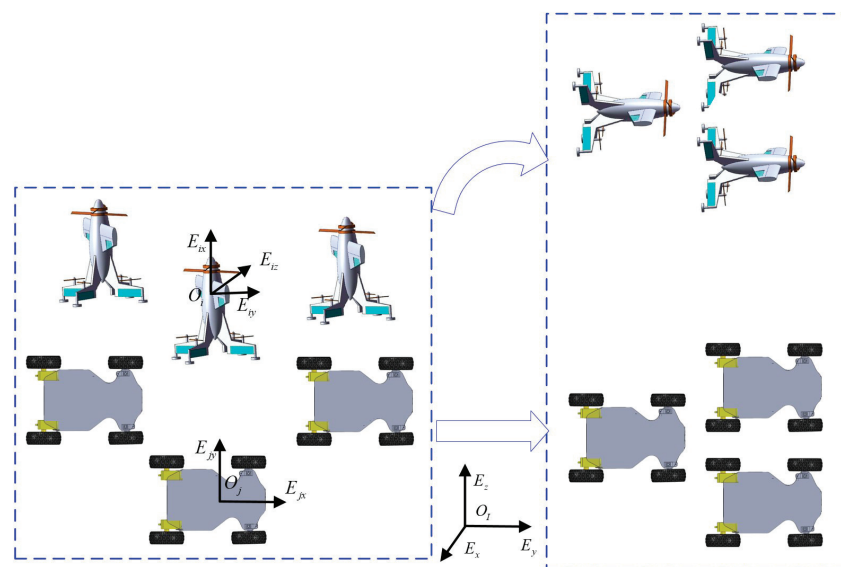


Figure 1. Cooperative platform integrating tail-sitter UAVs and UGVs.

To analyze the kinematics of the cooperative platform, two coordinate reference frames are established at the beginning. The global inertial reference frame is constructed as $E_I \triangleq \{O_I E_x E_y E_z\}$ and the vehicle-attached body reference frame is expressed as $E_i \triangleq \{O_i E_{ix} E_{iy} E_{iz}\}$. The rotational conversion matrix mapping the two reference frames is marked R_i . From [8], the i th tail-sitter dynamical equations are given as follows

$$\begin{aligned} m_{iu} \ddot{p}_{ip} &= F_{iu}, \\ J_i \dot{\omega}_i &= M_{iu} - \omega_i \times J_i \omega_i, \end{aligned} \quad (1)$$

where $p_{ip} = [p_{ip,x} \ p_{ip,y} \ p_{ip,z}]^T$ characterizes the inertial-frame position of the i th tail-sitter position, m_i denotes the i th tail-sitter mass, J_i describes inertia matrix, ω_i signifies the body-frame angular velocity, M_{iu} and F_{iu} are the total moment and force exerted on tail-sitter, respectively. In this paper, the attitude representation of the quaternion is used to avoid the singularities of Euler description. Define $q_i = [q_{i0} \ \bar{q}_i]^T = [q_{i0} \ q_{i1} \ q_{i2} \ q_{i3}]^T$ as the quaternion vector. The relation between quaternion q_i and angular velocity ω_i can be described as

$$\begin{aligned} \dot{\bar{q}}_i &= 0.5 \bar{q}_i \times \omega_i + 0.5 q_{i0} \omega_i, \\ \dot{q}_{i0} &= -0.5 \omega_i^T \bar{q}_i. \end{aligned} \quad (2)$$

The total force F_{iu} acting on the vehicle consists of gravity, aerodynamic action F_{if} , motor-generated thrust F_{ic} , and external interference F_{id} , can be written as

$$F_{iu} = R_i (F_{ic} + F_{if} + F_{id}) - mg c_{3,3}, \quad (3)$$

where $F_{ic} = [k_{it} \sum_{j=1}^4 \omega_{ij}^2 \ 0 \ 0]^T$ with k_{it} is the rotor thrust factor, ω_{ij} characterizes the angular rotating velocity of the four rotors, g represents the standard gravitational constant, and $c_{3,3} = [0 \ 0 \ 1]^T$. M_{iu} consists of four distinct torque components: control moment M_{ic} , aerodynamic load torque M_{iw} , gyroscopic coupling torque M_{ie} , and external interference torque M_{id} , can be formulated as

$$M_{iu} = M_{ic} + M_{iw} + M_{ie} + M_{id}. \quad (4)$$

M_{ic} is calculated as

$$M_{ic} = M_{ir} + M_{ia}, \quad (5)$$

where M_{ir} characterizes the rotational moment originating from rotors, M_{ia} represents the aerodynamic moment induced by the vehicle's airfoil structures. The formulations for M_{ir} and M_{ia} are given as

$$M_{ir} = \begin{bmatrix} \sum_{j=1}^4 (-1)^{j+1} a_{ir} \omega_{ij}^2 \\ l_{i1} a_{i\omega} \left[\sum_{j=1}^2 \omega_{ij}^2 - \sum_{j=3}^4 \omega_{ij}^2 \right] / 2 \\ l_{i2} a_{i\omega} \left[\sum_{j=2}^3 \omega_{ij}^2 - \omega_{i1}^2 - \omega_{i4}^2 \right] / 2 \end{bmatrix}, \quad (6)$$

$$M_{ia} = \begin{bmatrix} l_{i2} C_{i\sigma} S_{ir} \rho \cos \alpha_i (v_{ix}^2 + v_{iz}^2) (\omega_{i1} - \omega_{i2}) \\ l_{i3} C_{i\sigma} S_{ir} \rho \cos \alpha_i (v_{ix}^2 + v_{iz}^2) (\omega_{i1} + \omega_{i2}) \\ 0 \end{bmatrix}, \quad (7)$$

where a_{ir} , $a_{i\omega}$, l_{i1} , l_{i2} , l_{i3} , S_{ir} , and $C_{i\sigma}$ represent modeling constants, ρ denotes the air density, v_{ix} expresses longitudinal translational velocity measured within coordinate frame E_i , v_{iz} describes the vertical speed, α_i denotes angle of attack, and ω_{i1} , ω_{i2} describe static deflection bias angles of the vehicle's flaps.

From [26,27], the complete dynamic mathematical model of UGVs is formulated as

$$\begin{aligned}\ddot{p}_{ig,x} &= \dot{p}_{ig,y}\dot{\psi}_{ig} - \frac{C_{ig}}{m_{ig}}\dot{p}_{ig,x}^2 + \frac{1}{m_{ig}}F_{ig,x} + F_{ig,1}, \\ \ddot{p}_{ig,y} &= -\dot{p}_{ig,x}\dot{\psi}_{ig} + \frac{1}{m_{ig}}F_{ig,y} + F_{ig,2}, \\ \ddot{\psi}_{ig} &= \frac{1}{I_{ig}}M_{ig} + M_{ig,d},\end{aligned}\quad (8)$$

where $p_{ig,x}$, $p_{ig,y}$, and ψ_{ig} are the longitudinal position, lateral position, and yaw angle of the i th ground vehicle, respectively, m_{ig} represents the mass of this ground vehicle, C_{ig} is the aerodynamic drag coefficient, I_{ig} corresponds to the rotational inertia around the yaw axis, and $F_{ig,x}$, $F_{ig,y}$, M_{ig} are the total actuating forces and moment output from four tires, and $F_{ig,1}$, $F_{ig,2}$, $M_{ig,d}$ characterize external disturbance forces and disturbance torque. Let $u_{ig} = [F_{ig,x} \ F_{ig,y} \ M_{ig}]^T$, $p_{ig} = [p_{ig,x} \ p_{ig,y} \ \psi_{ig}]^T$, and $\Delta_{ig}^* = [F_{ig,1} \ F_{ig,2} \ M_{ig,d}]^T$. Then, the dynamic model for the ground vehicle platform can be reorganized as

$$\ddot{p}_{ig} = B_{ig}u_{ig} + D_{ig} + \Delta_{ig}^*, \quad (9)$$

where

$$B_{ig} = \begin{bmatrix} 1/m_{ig} & 0 & 0 \\ 0 & 1/m_{ig} & 0 \\ 0 & 0 & 1/I_{ig} \end{bmatrix}, D_{ig} = \begin{bmatrix} \dot{p}_{ig,y}\dot{\psi}_{ig} - \frac{C_{ig}}{m_{ig}}\dot{p}_{ig,x}^2 \\ -\dot{p}_{ig,x}\dot{\psi}_{ig} \\ 0 \end{bmatrix}.$$

2.3. Control Problem Statement

The heterogeneous air-ground swarm contains a virtual reference leader, n tail-sitter UAVs, and m ground vehicles. This virtual reference leader acts as the pinning anchor that generates the reference trajectory for the entire formation. Some tail-sitter UAVs and ground vehicles are treated as direct pinning agents that gain reference signals straight from the pinning anchor. The rest of vehicles connect to pinned nodes as adjacent nodes and gain indirect control to sustain the time-varying cooperative configuration.

Let $p_0^r = [p_{x0}^r \ p_{y0}^r \ p_{z0}^r]^T$ be the predefined path of the pinner, ψ_0^r be the yaw angle of the pinner. Define $p_{0g}^r = [p_{x0}^r \ p_{y0}^r \ \psi_0^r]^T$, $p_{0p}^r = [p_{x0}^r \ p_{y0}^r \ p_{z0}^r]^T$. Define the position tracking error of the i -th tail-sitter aircraft with respect to the pinned anchor as δ_{ip} , while δ_{ig} characterizes the state tracking error between the i -th ground platform and the pinned anchor. Accordingly, the inter-agent deviation between node i and node j is calculated via $\delta_{ijk} = \delta_{ik} - \delta_{jk}$ ($k = p, g$), and this expression reflects dynamically adjustable collaborative rules. Let $B_{ip} = m_{iu}^{-1}I_3$ and $B_{ia} = J_i^{-1}$, where I_n denotes an $n \times n$ identity matrix. In practical complex situations, related parameters inevitably deviate from the theoretical value. The parametric matrix terms B_{ip} , B_{ia} , and B_{ig} can be separated into two parts: $B_{ip} = B_{ip}^N + B_{ip}^\Delta$, $B_{ia} = B_{ia}^N + B_{ia}^\Delta$, and $B_{ig} = B_{ig}^N + B_{ig}^\Delta$, where B_{ip}^N , B_{ia}^N , and B_{ig}^N are nominal parameter matrices and B_{ip}^Δ , B_{ia}^Δ , and B_{ig}^Δ are the parametric deviations. For tail-sitter i , define $u_{ia} = M_{ic}$ and $u_{ip} = R_i F_{ic}$.

In this paper, the communication link is regarded as an ideal communication link added with the unknown corrupted uncertainties. The communication networks suffering from disturbances with the following expression:

$$\begin{aligned}w_{\sigma(t)}^{ij} &= \bar{w}_{\sigma(t)}^{ij} + w_{\sigma(t)}^{iu}, \\ d_{\sigma(t)}^{i0} &= \bar{d}_{\sigma(t)}^{i0} + d_{\sigma(t)}^{iu},\end{aligned}\quad (10)$$

where $\bar{w}_{\sigma(t)}^{ij}$ and $\bar{d}_{\sigma(t)}^{i0}$ correspond to baseline weights of adjustable communication links, $w_{\sigma(t)}^{iu}$ and $d_{\sigma(t)}^{iu}$ denote the time-varying uncertain corrupted weights, which pose additional control challenges for the cooperative system. For any switching signal $\sigma(t)$, the perturbed adjacency weight $w_{\sigma(t)}^{iu}$ and perturbed pinning weight $d_{\sigma(t)}^{iu}$ satisfy uniform bounded constraints: $|w_{\sigma(t)}^{iu}| \leq \bar{w}_u$, $|d_{\sigma(t)}^{iu}| \leq \bar{d}_u$, where $\bar{w}_u > 0$, $\bar{d}_u > 0$ are known positive constant upper bounds.

Then, the air-ground collaborative system models (1) and (9) can be re-expressed after adding disturbance uncertainty items as follows

$$\begin{aligned}\ddot{p}_{il} &= B_{il}^N u_{il} + D_{il}^N + \Delta_{il}, l = p, g, \\ \dot{\omega}_i &= -B_{ia}^N \omega_i^\times J_i^N \omega_i + B_{ia}^N u_{ia} + B_{ia}^N (M_{iw} + M_{ie}) + \Delta_{ia},\end{aligned}\quad (11)$$

where $D_{ip}^N = B_{ip}^N R_i F_{if} - g c_{3,3}$, Δ_{ip} , Δ_{ia} , and Δ_{ig} are expressed as follows

$$\begin{aligned}\Delta_{ip} &= B_{ip}^\Delta R_i F_{ic} + B_{ip}^\Delta R_i F_{if} + m_i^{-1} R_i F_{id} + \Delta_{ic}^p, \\ \Delta_{ia} &= B_{ia}^\Delta \omega_i^\times J_i^\Delta \omega_i + B_{ia}^\Delta \omega_i^\times J_i^N \omega_i + B_{ia}^\Delta u_{ia} \\ &\quad + B_{ia}^\Delta (M_{iw} + M_{ig}) + (J_i^N)^{-1} M_{id}, \\ \Delta_{ig} &= B_{ig}^\Delta u_{ig} + D_{ig}^\Delta + \Delta_{ig}^* + \Delta_{ic}^g,\end{aligned}\quad (12)$$

with Δ_{ic}^p and Δ_{ic}^g characterize the influences of uncertain communication links.

Remark 1. This paper develops a distinctive heterogeneous formation cooperative framework integrating tail-sitter aircraft and ground vehicles under switching topologies and uncertain communication links. The nonlinearities, ubiquitous disturbances, and parameter/state uncertainties are taken into account, simultaneously.

3. Robust Time-Varying Pinning Coordinated Controller Design

In this section, the cooperative control issue of heterogeneous tail-sitter UAVs and ground vehicles subject to parametric uncertainties and external perturbations is investigated. A robust time-varying pinning coordination controller is constructed to guarantee group cooperation under switching topologies and uncertain communication links.

The cooperative control input consists of three parts: the control part u_{il}^L ($l = p, g$) due to the pinner, the pinned-node relevant control item u_{il}^N , and the robust compensation part u_{il}^R that counteracts the negative effects of external disturbances and system uncertainties. Thus, the position control input of the i th aerial/ground vehicle u_{ip} has the following form as

$$u_{il} = u_{il}^L + u_{il}^N + u_{il}^R, (l = p, g). \quad (13)$$

u_{il}^L is designed as

$$\begin{aligned}u_{il}^L &= -\bar{d}_{\sigma(t)}^{i0} (B_{il}^N)^{-1} K_l (p_{il} - \delta_{il} - p_{0l}^r) \\ &\quad - \bar{d}_{\sigma(t)}^{i0} (B_{il}^N)^{-1} K_l (\dot{p}_{il} - \dot{\delta}_{il} - \dot{p}_{0l}^r), (l = p, g),\end{aligned}\quad (14)$$

where K_l , K_i denote positive definite gain matrices. In this paper, the nodes whose in-degrees are zero or out-degrees are bigger than their in-degrees are selected as pinning nodes.

u_{il}^N can be designed as

$$u_{il}^N = -\lambda_{il}(B_{il}^N)^{-1}K_l \left[\sum_{j \in N_{\sigma(t)}^{bi}} \bar{w}_{\sigma(t)}^{ij} (p_{il} - p_{jl} - \delta_{ijl}) \right] - \lambda_{il}(B_{il}^N)^{-1}K_l \left[\sum_{j \in N_{\sigma(t)}^{bi}} \bar{w}_{\sigma(t)}^{ij} (\dot{p}_{il} - \dot{p}_{jl} - \dot{\delta}_{ijl}) \right] - (B_{il}^N)^{-1}(D_{il}^N - \dot{\delta}_{il}), (l = p, g), \quad (15)$$

where λ_{il} represents a coupling parameter. Then, the term u_{il}^R is designed to mitigate the adverse influence brought by the deviation term Δ_{il} . The expression of u_{il}^R is given as

$$u_{il}^R(s) = -\left(B_{il}^N\right)^{-1}F_{il}(s)\Delta_{il}(s), (l = p, g), \quad (16)$$

where s is the Laplace operator, $F_{il}(s) = \text{diag}\{F_{il1}(s), F_{il2}(s), F_{il3}(s)\}$ with the following forms

$$F_{ilj}(s) = \frac{f_{il1}f_{il2}}{(s + f_{il1})(s + f_{il2})} (j = 1, 2, 3),$$

and f_{il1}, f_{il2} denote adjustable robust control gains. Actually, selecting appropriate values for these two gains allows $F_{ilj}(s) (j = 1, 2, 3)$ to achieve preset frequency bandwidth characteristics. The gain magnitudes of $F_{ilj}(s) (j = 1, 2, 3)$ can be adjusted near 1. In this case, u_{il}^R would approximate $-(B_{il}^N)^{-1}\Delta_{il}(s)$, and the influence of Δ_{il} would be reduced. For intricate missions, it is impossible to precisely characterize Δ_{il} via mathematical formulas. The realization of u_{il}^R does not rely on the concrete structure of Δ_{il} . According to (11), one can derive that

$$\Delta_{il} = \ddot{p}_{il} - B_{il}^N u_{il} - D_{il}^N, (l = p, g). \quad (17)$$

Integrating (16) with (17), one can achieve the time-domain formulation of u_{il}^R as follows:

$$\begin{aligned} \dot{\eta}_{il1} &= -f_{il2}\eta_{il1} - f_{il2}^2 p_{il} + B_{il}^N u_{il} + D_{il}^N, \\ \dot{\eta}_{il2} &= -f_{il1}\eta_{il2} + (f_{il1} + f_{il2})p_{il} + \eta_{il1}, \\ u_{il}^R &= (B_{il}^N)^{-1}f_{il1}f_{il2}(\eta_{il2} - p_{il}), (l = p, g), \end{aligned} \quad (18)$$

where η_{il1} and η_{il2} correspond to two states for u_{il}^R .

Remark 2. In fact, the uncertain communication link is regarded as an ideal communication link $\bar{w}_{\sigma(t)}^{ij}, \bar{d}_{\sigma(t)}^{i0}$ added with the unknown corrupted weights $w_{\sigma(t)}^{iu}, d_{\sigma(t)}^{iu}$. The effects of uncertain communication links are involved in $\Delta_{ic}^p, \Delta_{ic}^g$, whose negative impacts are suppressed via the constructed robust time-variant pinning control law. $\Delta_{ic}^p, \Delta_{ic}^g$ can be formulated as

$$\begin{aligned} \Delta_{ic}^l &= -(B_{il}^N)^{-1}K_l \left[\bar{d}_{\sigma(t)}^{iu} (p_{il} - \delta_{il} - p_{0l}^r) + \lambda_{il} \sum_{j \in N_{\sigma(t)}^{bi}} w_{\sigma(t)}^{iu} (p_{il} - p_{jl} - \delta_{ijl}) \right] \\ &\quad - (B_{il}^N)^{-1}K_l \left[\bar{d}_{\sigma(t)}^{iu} (\dot{p}_{il} - \dot{\delta}_{il} - \dot{p}_{0l}^r) + \lambda_{il} \sum_{j \in N_{\sigma(t)}^{bi}} w_{\sigma(t)}^{iu} (\dot{p}_{il} - \dot{p}_{jl} - \dot{\delta}_{ijl}) \right], l = p, g. \end{aligned}$$

For tail-sitter UAVs, one can define $e_{ia} = \begin{bmatrix} e_{iQ} & e_{i\omega} \end{bmatrix}^T = \begin{bmatrix} \tilde{Q}_i & \omega_i - \omega_i^r \end{bmatrix}^T$ as the attitude error according to [28], where ω_i^r represents the desired angular velocity, $\tilde{Q}_i$ denotes a function of quaternion q_i . The conversion from the translational command to the desired attitude can be found in [29].

For each tail-sitter, the objective of attitude control design is to sustain the intrinsic stable rotational dynamics of the aircraft. The proposed attitude control strategy only utilizes the self-state data of each tail-sitter, without requiring state data from other pinned nodes. Then, the resulting attitude control formulation is given by

$$u_{ia} = (B_{ia}^N)^{-1} (-K_a e_{iQ} - K_{\dot{a}} e_{i\omega} + \dot{\omega}_i^r) + \omega_i \times J_i^N \omega_i - (M_{i\omega} + M_{ie}) + u_{ia}^R, \quad (19)$$

where K_a and $K_{\dot{a}}$ denote the controller gain matrices, u_{ia}^R is the robust controller.

In a similar way to the position controller, u_{ia}^R is constructed as follows:

$$u_{ia}^R(s) = -\left(B_{ia}^N\right)^{-1} F_{ia}(s) \Delta_{ia}(s), \quad (20)$$

where $F_{ia}(s) = \text{diag}\{F_{ia1}(s), F_{ia2}(s), F_{ia3}(s)\}$ and

$$F_{iaj}(s) = \frac{f_{ia1} f_{ia2}}{(s + f_{ia1})(s + f_{ia2})} (j = 1, 2, 3),$$

with f_{ia1}, f_{ia2} represent the parameters for the robust controller. In a manner comparable to u_{ip}^R , one can acquire the finite-domain realization of u_{ia}^R using this identical procedure.

Remark 3. The developed cooperative architecture enables complicated mission execution within diverse conditions, which outperforms conventional air-ground cooperative architectures. In practical applications, the tail-sitters as an air formation platform can provide the relative horizontal trajectories for the team of ground vehicles. The ground vehicles can follow the relative horizontal trajectories, while maintaining a desired cooperative formation behavior and providing a safe take-off and landing platform.

Remark 4. In this paper, the coupled dynamics of tail-sitter aircraft and ground vehicles are considered in the dynamical model. The influences induced by coupling expressions $\omega_i^\times J_i^N \omega_i$ and D_{ig}^N are eliminated by the constructed control law $u_{il}^N (l = p, g)$. Besides, other coupled terms such as $B_{ip}^\Delta R_i F_{if}$, $B_{ia}^\Delta \omega_i^\times J_i^\Delta \omega_i$, and D_{ig}^Δ are integrated into lumped disturbances Δ_{ip} , Δ_{ia} , and Δ_{ig} following (12). The unfavorable influence of these lumped perturbations over the closed-loop control architecture can be restrained by the control input $u_{il}^R (l = p, g)$.

Remark 5. In fact, Theorem 1 provides theoretically conservative bounds for robust control parameters. In practical applications, one can utilize a single-direction online adjustment strategy to tune these gain parameters. Start with preset initial parameters and test the closed-loop control plant. If the system tracking and stability metrics fail to satisfy requirements, gradually enlarge f_{ik1} and $f_{ik2} (k = p, a, g)$ until ideal control effects are reached. In addition, the computational complexity of the proposed control law approximates that of the classical proportional-integral-derivative (PID) regulator. Therefore, it is comparatively easy to be implemented.

4. Robust Property Analysis

Let $e_{ipu} = p_{ip} - p_0^r - \delta_{ip}$, $e_{ipg} = p_{ig} - p_{ig}^r - \delta_{ig}$ be the tracking errors of tail-sitters and ground vehicles, respectively. Let $e_{ip} = \begin{bmatrix} e_{ipu}^T & e_{ipu}^T \end{bmatrix}^T$, $e_{ig} = \begin{bmatrix} e_{ipg}^T & e_{ipg}^T \end{bmatrix}^T$. Combining (9), (12), (13), (17), and (18) yields that

$$\begin{aligned}\dot{e}_{ip} &= A_{ip}e_{ip} - \lambda_{ip}B_{k1}K_pE_{ip} - \lambda_{ip}B_{k1}K_p\dot{E}_{ip} + B_{k1}\left(B_{ip}^Nu_{ip}^R + \Delta_{ip}\right), \\ \dot{e}_{ia} &= A_{ia}e_{ia} + B_{k1}\left(B_{ia}^Nu_{ia}^R + \Delta_{ia}\right), \\ \dot{e}_{ig} &= A_{ig}e_{ig} - \lambda_{ig}B_{k1}K_gE_{ig} - \lambda_{ig}B_{k1}K_g\dot{E}_{ig} + B_{k1}\left(B_{ig}^Nu_{ig}^R + \Delta_{ig}\right),\end{aligned}\quad (21)$$

where $E_{ip} = \sum_{j \in N_{\sigma(t)}^{bi}} \bar{w}_{\sigma(t)}^{ij}(e_{ipu} - e_{jpu}) + \bar{d}_{\sigma(t)}^{i0}e_{ipu}$, $E_{ig} = \sum_{j \in M_{\sigma(t)}^{bi}} \bar{w}_{\sigma(t)}^{ij}(e_{ipg} - e_{jpg}) + \bar{d}_{\sigma(t)}^{i0}e_{ipg}$, and

$$\begin{aligned}A_{ip} &= A_{ig} = \begin{bmatrix} 0_{3 \times 3} & I_3 \\ 0_{3 \times 3} & 0_{3 \times 3} \end{bmatrix}, \\ A_{ia} &= \begin{bmatrix} 0_{3 \times 3} & I_3 \\ -K_a & -K_{\dot{a}} \end{bmatrix}, B_{k1} = \begin{bmatrix} 0_{3 \times 3} \\ I_3 \end{bmatrix}.\end{aligned}$$

Then, it follows that

$$\begin{aligned}\dot{e}_p &= A_p^{\sigma(t)}e_p + B_{k2}\left(B_{ip}^Nu_{ip}^R + \Delta_{ip}\right), \\ \dot{e}_a &= A_a^{\sigma(t)}e_a + B_{k2}\left(B_{ia}^Nu_{ia}^R + \Delta_{ia}\right), \\ \dot{e}_g &= A_g^{\sigma(t)}e_g + B_{k2}\left(B_{ig}^Nu_{ig}^R + \Delta_{ig}\right),\end{aligned}\quad (22)$$

where $e_p = [e_{1p}^T, e_{2p}^T, \dots, e_{np}^T]^T$, $e_a = [e_{1a}^T, e_{2a}^T, \dots, e_{na}^T]^T$, $e_g = [e_{1g}^T, e_{2g}^T, \dots, e_{ng}^T]^T$, and

$$\begin{aligned}A_p^{\sigma(t)} &= I_n \otimes A_{ip} - \lambda_{ip}\left(L_{\sigma(t)}^p + B_{Lp}\right) \otimes B_{k1}K_{tp}, \\ A_a^{\sigma(t)} &= I_n \otimes A_{ia}, B_{k2} = I_n \otimes B_{k1}, \\ A_g^{\sigma(t)} &= I_m \otimes A_{ig} - \lambda_{ig}\left(L_{\sigma(t)}^g + B_{Lg}\right) \otimes B_{k1}K_{tg},\end{aligned}$$

with $B_{Lp} = \text{diag}\left\{\bar{d}_{\sigma(t)}^{i0}\right\} \in \mathbb{R}^{N \times N}$, $B_{Lg} = \text{diag}\left\{\bar{d}_{\sigma(t)}^{i0}\right\} \in \mathbb{R}^{M \times M}$, $K_{tp} = \begin{bmatrix} K_p & K_{\dot{p}} \end{bmatrix}$, and $K_{tg} = \begin{bmatrix} K_g & K_{\dot{g}} \end{bmatrix}$.

Theorem 1. Consider the constructed heterogeneous air-ground cooperative system in (11). The desired cooperative configuration is guaranteed to be achieved under switching topologies and multiple uncertainties by utilizing the developed robust time-varying pinning coordinated controller in Section 3. Furthermore, $\forall \varepsilon > 0, \exists t_0 > 0, T > 0, f_p^* > 0, f_a^* > 0, f_g^* > 0$, if $f_{ip1} >> f_{ip2} \geq f_p^*$, $f_{ia1} >> f_{ia2} \geq f_a^*$, and $f_{ig1} >> f_{ig2} \geq f_g^*$, $e_k(t)$ ($k = p, a, g$) are uniformly bounded for $t \geq t_0$ and $\|e_k(t)\| \leq \varepsilon, \forall t \geq T$.

Proof. Define

$$\begin{aligned}\Pi_{ik}(s) &= \frac{s + f_{ik1} + f_{ik2}}{(s + f_{ik1})(s + f_{ik2})} \Delta_{ik}(s), \\ \Theta_k(s) &= e_k(s) - B_{k2}\Pi_k(s), k = p, a, g.\end{aligned}\quad (23)$$

From (22) and (23), one can obtain that

$$\dot{\Theta}_k = A_k^{\sigma(t)}\Theta_k + A_k^{\sigma(t)}B_{k2}\Pi_k, (k = p, a, g), \quad (24)$$

where $\Pi_p = [\Pi_{ip}^T \cdots \Pi_{np}^T]^T$, $\Pi_a = [\Pi_{1a}^T \cdots \Pi_{na}^T]^T$, $\Pi_g = [\Pi_{1g}^T \cdots \Pi_{mg}^T]^T$. From (23), $\Pi_{ik}(k = p, a, g)$ can be written in time domain as

$$\begin{aligned}\dot{\vartheta}_{ik1} &= -f_{ik2}\vartheta_{ik1} + \frac{f_{ik1}}{f_{ik1} - f_{ik2}}\Delta_{ik}, \\ \dot{\vartheta}_{ik2} &= -f_{ik1}\vartheta_{ik2} + \frac{f_{ik2}}{f_{ik1} - f_{ik2}}\Delta_{ik}, \\ \Pi_{ik} &= \begin{bmatrix} I_3 & -I_3 \end{bmatrix} \begin{bmatrix} \vartheta_{ik1} \\ \vartheta_{ik2} \end{bmatrix},\end{aligned}\quad (25)$$

where ϑ_{ik1} and ϑ_{ik2} denote two state variables. Then, the robust control input $u_{ik}^R(k = p, a, g)$ can be rewritten as

$$u_{ik}^R = -\left(B_{ik}^N\right)^{-1} \begin{bmatrix} f_{ik2}I_3 & -f_{ik1}I_3 \end{bmatrix} \begin{bmatrix} \vartheta_{ik1} \\ \vartheta_{ik2} \end{bmatrix}. \quad (26)$$

Let $\vartheta_{p1} = [\vartheta_{1p1}^T \cdots \vartheta_{np1}^T]^T$, $\vartheta_{a1} = [\vartheta_{1a1}^T \cdots \vartheta_{na1}^T]^T$, $\vartheta_{g1} = [\vartheta_{1g1}^T \cdots \vartheta_{mg1}^T]^T$, $\vartheta_{p2} = [\vartheta_{1p2}^T \cdots \vartheta_{np2}^T]^T$, $\vartheta_{a2} = [\vartheta_{1a2}^T \cdots \vartheta_{na2}^T]^T$, $\vartheta_{g2} = [\vartheta_{1g2}^T \cdots \vartheta_{mg2}^T]^T$. Let $f_{k1} = f_{ik1}(k = p, a, g)$, $f_{k2} = f_{ik2}$. Then,

$$\begin{aligned}\dot{\vartheta}_{k1} &= A_{k1}\vartheta_{k1} + B_{k1}\Delta_k, \\ \dot{\vartheta}_{k2} &= A_{k2}\vartheta_{k2} + B_{k2}\Delta_k, \\ \Pi_k &= \begin{bmatrix} I_l & -I_l \end{bmatrix} \begin{bmatrix} \vartheta_{k1} \\ \vartheta_{k2} \end{bmatrix}, l = \begin{cases} 3n, k = p, a, \\ 3m, k = g, \end{cases}\end{aligned}\quad (27)$$

where $A_{p1} = -f_{p2}I_n$, $A_{a1} = -f_{a2}I_n$, $A_{g1} = -f_{g2}I_m$, $A_{p2} = -f_{p1}I_n$, $A_{a2} = -f_{a1}I_n$, $A_{g2} = -f_{g1}I_m$, $B_{p1} = f_{p1}I_n/(f_{p1} - f_{p2})$, $B_{a1} = f_{a1}I_n/(f_{a1} - f_{a2})$, $B_{g1} = f_{g1}I_m/(f_{g1} - f_{g2})$, $B_{p2} = f_{p2}I_n/(f_{p1} - f_{p2})$, $B_{a2} = f_{a2}I_n/(f_{a1} - f_{a2})$, $B_{g2} = f_{g2}I_m/(f_{g1} - f_{g2})$, $\Delta_p = [\Delta_{1p}^T \cdots \Delta_{np}^T]^T$, $\Delta_a = [\Delta_{1a}^T \cdots \Delta_{na}^T]^T$, and $\Delta_g = [\Delta_{1g}^T \cdots \Delta_{mg}^T]^T$. In practical applications, $A_k^{\sigma(t)}$ is a stable matrix by selecting proper controller parameters. Thus, there exists a positive definite matrix $P_k^{\sigma(t)}$ satisfying that $P_k^{\sigma(t)}A_k^{\sigma(t)} + \left(A_k^{\sigma(t)}\right)^T P_k^{\sigma(t)} = -I_l$, where $l = 6n$ when $k = p, a$ and $l = 6m$ when $k = g$. Constructing the following Lyapunov function as

$$V(t) = \sum_{k=p,a,g} \Theta_k^T(t) P_k^{\sigma(t)} \Theta_k(t) + \sum_{k=p,a,g} (\vartheta_{k1}^T(t) \vartheta_{k1}(t) + \vartheta_{k2}^T(t) \vartheta_{k2}(t)). \quad (28)$$

Let

$$\begin{aligned}V_1(t) &= \sum_{k=p,a,g} \Theta_k^T(t) P_k^{\sigma(t)} \Theta_k(t), \\ V_2(t) &= \sum_{k=p,a,g} (\vartheta_{k1}^T(t) \vartheta_{k1}(t) + \vartheta_{k2}^T(t) \vartheta_{k2}(t)).\end{aligned}$$

Taking time derivative for $V_1(t)$ yields that

$$\dot{V}_1(t) \leq - \sum_{k=p,a,g} \|\Theta_k\|^2 + \sum_{k=p,a,g} \left(2\pi_f \|\Theta_k\| \|\vartheta_{k1}\| + 2\pi_f \|\Theta_k\| \|\vartheta_{k2}\| \right), \quad (29)$$

where π_f is a positive constant. By differentiating $V_2(t)$ with respect to time, one has

$$\begin{aligned} \dot{V}_2(t) = & - \sum_{k=p,a,g} 2f_{k2} \|\vartheta_{k1}\|^2 - \sum_{k=p,a,g} 2f_{k1} \|\vartheta_{k2}\|^2 + \sum_{k=p,a,g} \frac{2f_{k2}}{f_{k1} - f_{k2}} \|\vartheta_{k1}\| \|\Delta_k\| \\ & + \sum_{k=p,a,g} \frac{2f_{k1}}{f_{k1} - f_{k2}} \|\vartheta_{k2}\| \|\Delta_k\|. \end{aligned} \quad (30)$$

From (11), one can obtain that

$$\|\Delta_k\| \leq \zeta_1 \|\Theta_k\| + \zeta_2 \|\vartheta_{k1}\| + \zeta_3 \|\vartheta_{k2}\| + \zeta_4. \quad (31)$$

From (28)–(31), one can have that

$$\begin{aligned} \dot{V}(t) \leq & - \sum_{k=p,a,g} \|\Theta_k\|^2 + \sum_{k=p,a,g} \left(-2f_{k2} + \frac{2\zeta_2 f_{k2}}{f_{k1} - f_{k2}} \right) \|\vartheta_{k1}\|^2 \\ & + \sum_{k=p,a,g} \left(-2f_{k1} + \frac{2\zeta_3 f_{k1}}{f_{k1} - f_{k2}} \right) \|\vartheta_{k2}\|^2 + \sum_{k=p,a,g} \left(2\pi_f + \frac{2\zeta_1 f_{k2}}{f_{k1} - f_{k2}} \right) \|\Theta_k\| \|\vartheta_{k1}\| \\ & + \sum_{k=p,a,g} \left(2\pi_f + \frac{2\zeta_1 f_{k1}}{f_{k1} - f_{k2}} \right) \|\Theta_k\| \|\vartheta_{k2}\| + \sum_{k=p,a,g} \frac{2\zeta_3 f_{k2} + 2\zeta_2 f_{k1}}{f_{k1} - f_{k2}} \|\vartheta_{k1}\| \|\vartheta_{k2}\| \\ & + \sum_{k=p,a,g} \frac{2\zeta_4 f_{k2}}{f_{k1} - f_{k2}} \|\vartheta_{k1}\| + \sum_{k=p,a,g} \frac{2\zeta_4 f_{k1}}{f_{k1} - f_{k2}} \|\vartheta_{k2}\|. \end{aligned} \quad (32)$$

Let $W_k = \begin{bmatrix} \|\Theta_k\| & \sqrt{f_{k1}} \|\vartheta_{k1}\| & \sqrt{f_{k1}} \|\vartheta_{k2}\| \end{bmatrix}^T$ and $1 > \tau > 0$, one has that

$$\begin{aligned} \dot{V}(t) \leq & -\tau V - \sum_{k=p,a,g} (1-\tau) \|\Theta_k\|^2 - \sum_{k=p,a,g} \left(-\frac{2f_{k2}}{f_{k1}} + \frac{2\zeta_2 f_{k2}}{f_{k1}(f_{k1} - f_{k2})} + \frac{\tau}{f_{k1}} \right) \|\vartheta_{k1}\|^2 \\ & + \sum_{k=p,a,g} \left(-2 + \frac{2\zeta_3}{f_{k1} - f_{k2}} + \frac{\tau}{f_{k1}} \right) \|\vartheta_{k2}\|^2 + \sum_{k=p,a,g} \left(\frac{2\pi_f}{\sqrt{f_{k1}}} + \frac{2\zeta_1 f_{k2}}{\sqrt{f_{k1}}(f_{k1} - f_{k2})} \right) \|\Theta_k\| \|\vartheta_{k1}\| \\ & + \sum_{k=p,a,g} \left(\frac{2\pi_f}{\sqrt{f_{k1}}} + \frac{2\zeta_1 \sqrt{f_{k1}}}{f_{k1} - f_{k2}} \right) \|\Theta_k\| \|\vartheta_{k2}\| + \sum_{k=p,a,g} \frac{2\zeta_3 f_{k2} + 2\zeta_2 f_{k1}}{f_{k1}(f_{k1} - f_{k2})} \|\vartheta_{k1}\| \|\vartheta_{k2}\| \\ & + \sum_{k=p,a,g} \frac{2\zeta_4(f_{k1} + f_{k2})}{\sqrt{f_{k1}}(f_{k1} - f_{k2})} \\ \leq & -\tau V + \sum_{k=p,a,g} W_k^T \Xi W_k + \varepsilon_0, \end{aligned} \quad (33)$$

$$\begin{aligned} \text{where } \varepsilon_0 = & \sum_{k=p,a,g} \frac{2\zeta_4(f_{k1} + f_{k2})}{\sqrt{f_{k1}}(f_{k1} - f_{k2})}, \Xi \in \mathbb{R}^{3 \times 3} \text{ with } \Xi_{11} = -(1-\tau), \Xi_{22} = -\frac{2f_{k2}}{f_{k1}} + \\ & \frac{2\zeta_2 f_{k2}}{f_{k1}(f_{k1} - f_{k2})} + \frac{\tau}{f_{k1}}, \Xi_{33} = -2 + \frac{2\zeta_3}{f_{k1} - f_{k2}} + \frac{\tau}{f_{k1}}, \Xi_{12} = \Xi_{21} = \frac{\pi_f}{\sqrt{f_{k1}}} + \frac{\zeta_1 f_{k2}}{\sqrt{f_{k1}}(f_{k1} - f_{k2})}, \\ & \Xi_{13} = \Xi_{31} = \frac{\pi_f}{\sqrt{f_{k1}}} + \frac{\zeta_1 \sqrt{f_{k1}}}{f_{k1} - f_{k2}}, \Xi_{23} = \Xi_{32} = \frac{\zeta_3 f_{k2} + \zeta_2 f_{k1}}{f_{k1}(f_{k1} - f_{k2})}. \end{aligned}$$

If $f_{k1} \gg f_{k2} > 0$ ($k = p, a, g$), one sees that $\Xi < 0$. Then, one has that

$$V(t) \leq V(t_0) e^{-\tau(t-t_0)} + \varepsilon_1, \quad (34)$$

where $\varepsilon_1 = (1 - e^{-\tau(t-t_0)}) \varepsilon_0 / \tau$. According to (23), it yields that

$$\begin{aligned} \|e_k\|^2 \leq & 2\|\Theta_k\|^2 + 4\|B_{k2}\|^2 (\|\vartheta_{k1}\|^2 + \|\vartheta_{k2}\|^2) \\ \leq & \max \left\{ \frac{2}{\lambda_{\min}^p}, 4\|B_{k2}\|^2 \right\} \cdot (V_1(t) + V_2(t)) \\ = & \tau_0 V(t), \end{aligned} \quad (35)$$

where $\tau_0 = \max\left\{\frac{2}{\lambda_{\min}^p}, 4\|B_{k2}\|^2\right\}$, $\lambda_{\min}^p = \min_{\sigma(t)} \lambda_{\min}(P_k^{\sigma(t)})$. Then, one sees that $\forall \varepsilon > 0$, $\exists t_0 > 0, T > 0, f_p^* > 0, f_a^* > 0, f_g^* > 0$, if $f_{ip1} \gg f_{ip2} \geq f_p^*, f_{ia1} \gg f_{ia2} \geq f_a^*$, and $f_{ig1} \gg f_{ig2} \geq f_g^*$, $e_k(t)$ ($k = p, a, g$) are uniformly bounded for $t \geq t_0$ and $\|e_k(t)\| \leq \varepsilon, \forall t \geq T$. $\square$

Remark 6. In fact, the stability of the constructed heterogeneous air-ground cooperative system at switching instants can be guaranteed by selecting the minimum dwell time $t_{\Delta m}$ to satisfy $\tau_{\Delta m} > \ln \mu / \tau$, where $\mu > 1$. The Lyapunov function satisfies globally bounded growth across all switching instants.

Remark 7. It can be concluded based on Theorem 1 that desirable tracking accuracy and anti-disturbance robustness are guaranteed under switching topologies and multiple uncertainties by appropriately adjusting control parameters. The whole-system tracking errors converge rapidly to a small bounded region within finite time. Moreover, the designed cooperative controller is more intuitive and simple in structure.

Remark 8. In this paper, the heterogeneous air-ground cooperative system with switching topologies and uncertain communication links was considered. The constructed robust pinning-coordinated controller can realize the time-varying coordination scenario under switching topologies and uncertain communication links. However, the communication interactions are time-invariant in previous studies [18–21,30], which are limited in practical tasks.

Remark 9. In [31,32], the finite-time coordination control schemes of multi-agent networks are presented, which exhibit better applicability to complicated real conditions. In [33], the global asymptotic stability criteria for feedback optimization systems were constructed. Ref. [34] investigated quadrotor cooperative control under fixed communication constraints. These studies offer valuable insights for this paper.

5. Simulation Results

In this section, the simulation validation is carried out for the developed air-ground system utilizing the proposed robust time-varying pinning coordinated controller. The tail-sitter parameters are depicted in [8], and the ground vehicle parameters are shown in [26]. Consider a time-varying coordination scenario with three tail-sitters and three ground vehicles under switching topologies, disturbances, and uncertainties. At the beginning, tail-sitter UAVs perform vertical take-off operations in linear arrays above their matched ground vehicles, then the formation shape transforms into a triangle, and the ground platforms track tail-sitter aircraft's horizontal relative paths to accomplish coordinated control tasks. The switching connection topologies of the air-ground systems are represented in Figure 2, where labels 1, 2, and 3 denote the three tail-sitters, labels 4, 5, and 6 denote the three UGVs, respectively.

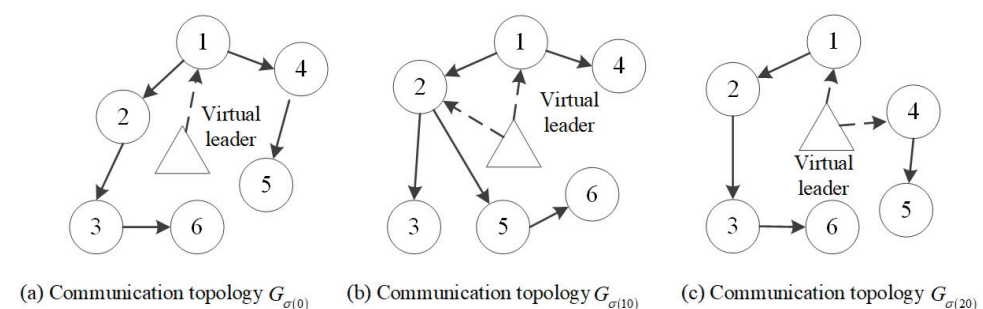


Figure 2. Switching communication topology.

During the coordination mission, the graphs among the heterogeneous vehicle group are described as $G_{\sigma(0)}$, $G_{\sigma(10)}$, and $G_{\sigma(20)}$. The weighted matrix $W_{\sigma(t)}$ can be described as $W_{\sigma(t)} = [\chi(t) - \chi(t-10)]W_1 + [\chi(t-10) - \chi(t-20)]W_2 + \chi(t-20)W_3$, where $\chi(t) = 1$ if $t > 0$, otherwise $\chi(t) = 0$. Therefore, the Laplacian matrix can be obtained as

$$L_a = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix}, L_b = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & -1 & 2 \end{bmatrix}, L_c = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix}.$$

For the coordination case, the pinning coefficients are expressed as $d_{\sigma(t)}^{10} = 1 + 0.5 \sin(t)$, $d_{\sigma(t)}^{20} = \chi(t-10) - \chi(t-20) + 0.5 \sin(t)$, $d_{\sigma(t)}^{40} = \chi(t-20) + 0.5 \sin(t)$, $d_{\sigma(t)}^{30} = d_{\sigma(t)}^{50} = d_{\sigma(t)}^{60} = 0$, where $\chi(t) = 1$ if $t > 0$, otherwise $\chi(t) = 0$. All parametric deviations are capped at 25% of their corresponding nominal values. The external disturbances are chosen as $F_{ig,1} = 1.5 \sin(2t) + 1.5 \cos(t)$, $F_{ig,2} = 0.6 \sin(t) + 0.6 \cos(2t)$, $M_{ig,d} = 0.8 \sin(2t) + 0.8 \cos(t)$, and

$$F_{id} = \begin{bmatrix} 12 \sin(2t) + 16 \cos(t) \\ 15 \sin(2t) + 25 \cos(t) \\ 12 \sin(t) + 20 \cos(2t) \end{bmatrix}, M_{id} = \begin{bmatrix} 9 \sin(t) + 3 \cos(2t) \\ 10 \sin(t) + 6 \cos(2t) \\ 15 \sin(2t) + 9 \cos(t) \end{bmatrix}.$$

For the heterogeneous aerial-ground integrated collaborative system, the initial state parameters are given as: $p_{1p}(0) = [0 \ 6 \ 0]^T$, $p_{2p}(0) = [0 \ 0 \ 0]^T$, $p_{3p}(0) = [0 \ -6 \ 0]^T$, $q_i(0) = [\sqrt{2}/2 \ 0 \ \sqrt{2}/2 \ 0]^T$, $p_{1g}(0) = [0 \ 6 \ 0]^T$, $p_{2g}(0) = [0 \ 0 \ 0]^T$, and $p_{3g}(0) = [0 \ -6 \ 0]^T$. The designed controller parameters are given as: $f_{ip1} = 500$, $f_{ip2} = 100$, $f_{ia1} = 100$, $f_{ia2} = 10$, $f_{ig1} = 120$, $f_{ig2} = 10$, $K_a = \text{diag}\{130, 120, 130\}$, $K_{\dot{a}} = \text{diag}\{116, 121, 106\}$, $K_p = \text{diag}\{2.8, 3.8, 2.8\}$, $K_{\dot{p}} = \text{diag}\{1, 1.3, 1\}$, $K_g = \text{diag}\{320.2, 320.2, 320.2\}$, and $K_{\dot{g}} = \text{diag}\{220.1, 220.1, 220.1\}$. Predefined trajectory deviations are set as: $\delta_{1p} = [0 \ 6 \ 0]^T$, $\delta_{3p} = [0 \ -6 \ 0]^T$, $\delta_{1g} = [0 \ 6 \ 0]^T$, $\delta_{3g} = [0 \ -6 \ 0]^T$, $\delta_{2p} = [0 \ 0 \ 0]^T$, $\delta_{2g} = [0 \ 0 \ 0]^T$, when $t < 10$, and $\delta_{1p} = [0 \ 6 \ 0]^T$, $\delta_{3p} = [0 \ -6 \ 0]^T$, $\delta_{1g} = [0 \ 6 \ 0]^T$, $\delta_{3g} = [0 \ -6 \ 0]^T$, $\delta_{2p} = [12 - 12e^{-(t-10)} \ 0 \ 0]^T$, $\delta_{2g} = [12 - 12e^{-(t-10)} \ 0 \ 0]^T$, when $t \geq 10$.

Figure 3 illustrates the coordination trajectory utilizing the developed controller. Figure 4 shows the attitude response of tail-sitters. The trajectory tracking errors of these tail-sitters and ground vehicles are depicted in Figure 5 and Figure 6, respectively. Furthermore, a baseline controller [35] is applied to indicate the superiority of the developed scheme. The corresponding tracking errors of tail-sitters and ground vehicles are depicted in Figures 7 and 8, respectively. From the results, one can see that the maximum steady-state position tracking error of tail-sitters using the proposed controller is controlled within 0.3 m during the flight mission. The maximum tracking error is limited to 0.1 m for UGVs, with no obvious oscillation divergence when communication weights contain time-varying corruption terms. However, under identical simulation conditions, the baseline controller produces maximum position tracking errors up to 5 m for tail-sitters and 2 m for ground vehicles, accompanied by persistent large-amplitude oscillations. The practical trajectory using the baseline controller deviates from the desired trajectory. The proposed robust

controller can obtain better performance compared to the baseline controller under the same conditions, involving switching topologies, uncertainties, and ambient disturbances.

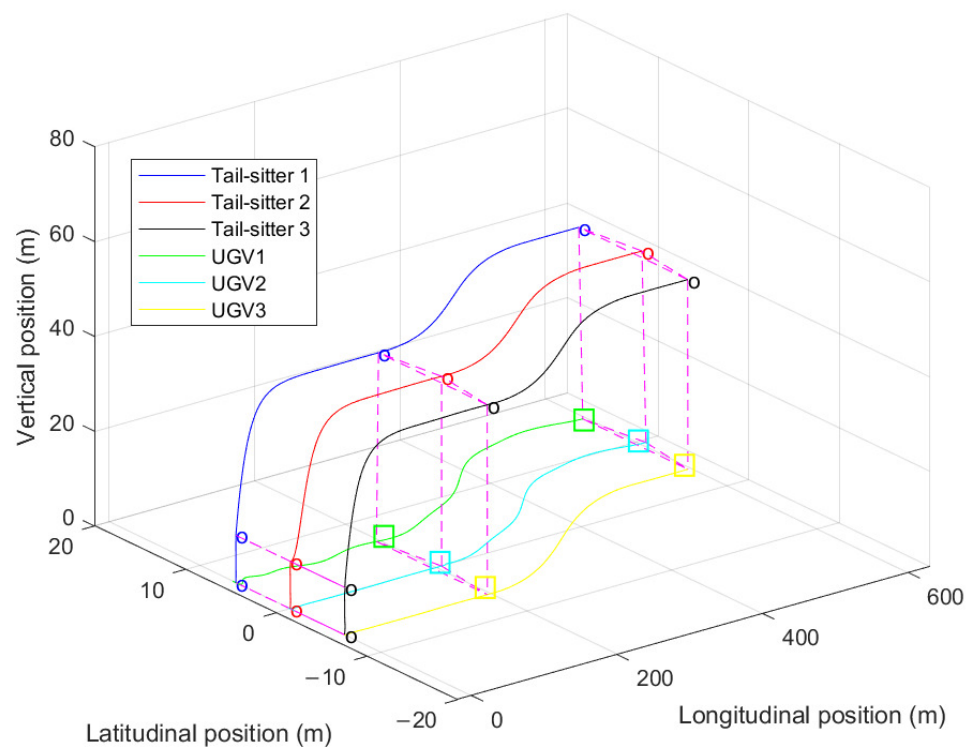


Figure 3. Coordination trajectory (proposed controller).

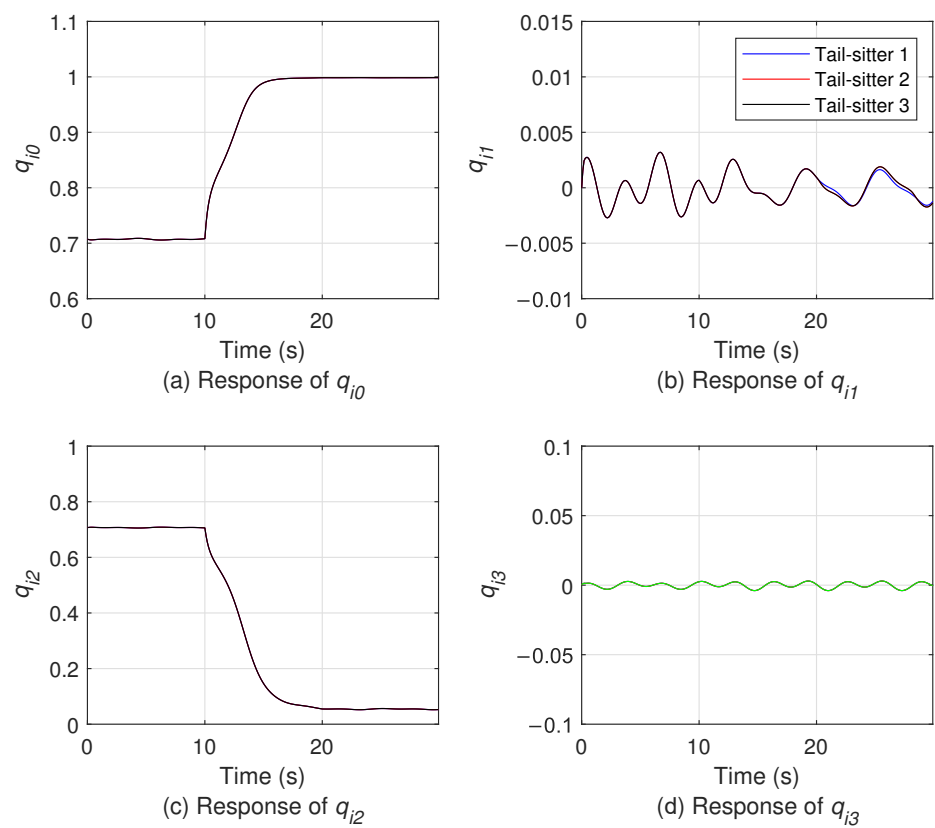


Figure 4. Attitude response (proposed controller).

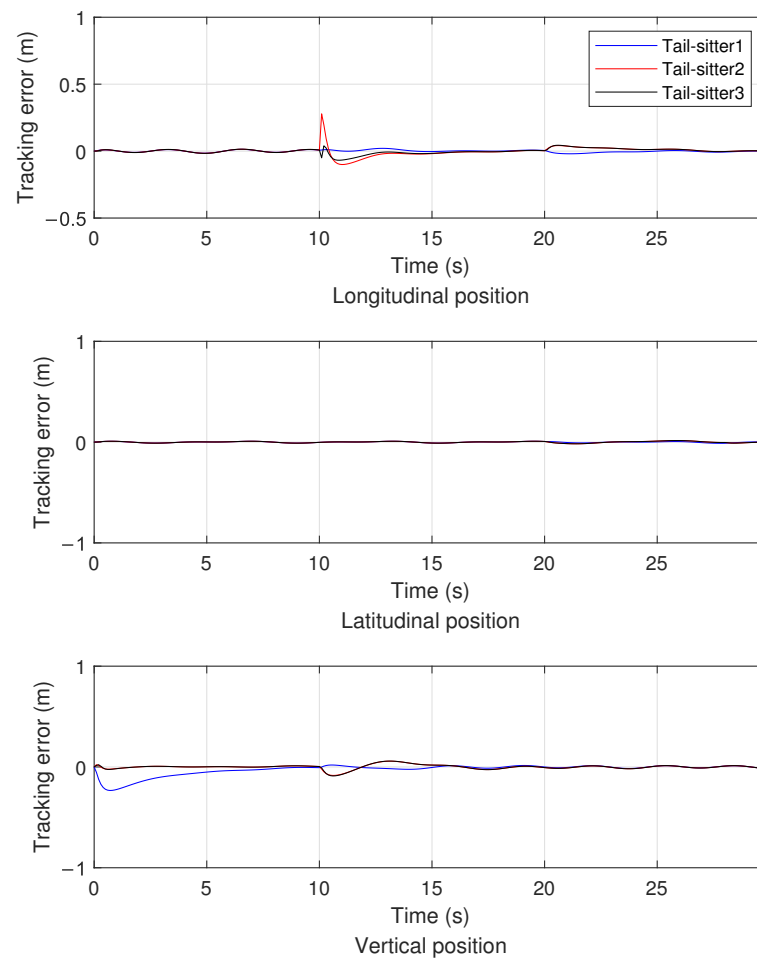


Figure 5. Position errors of tail-sitters (proposed controller).

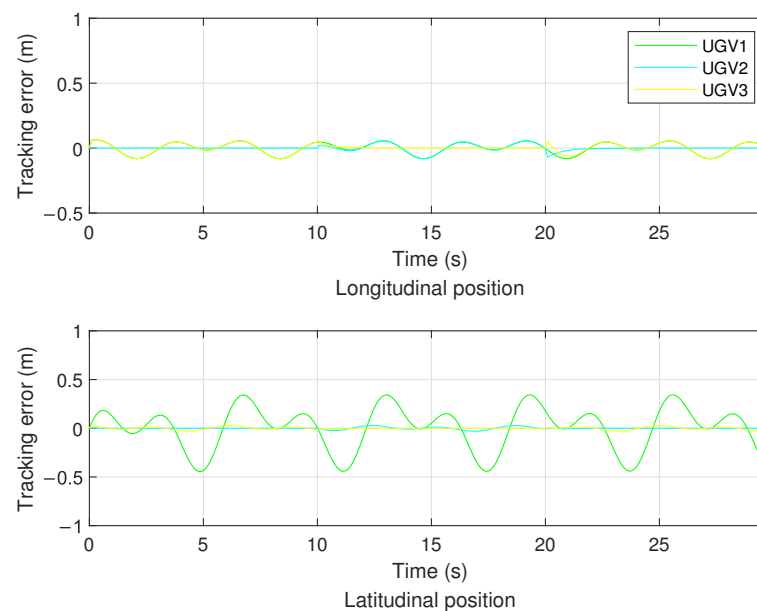


Figure 6. Position errors of UGVs (proposed controller).

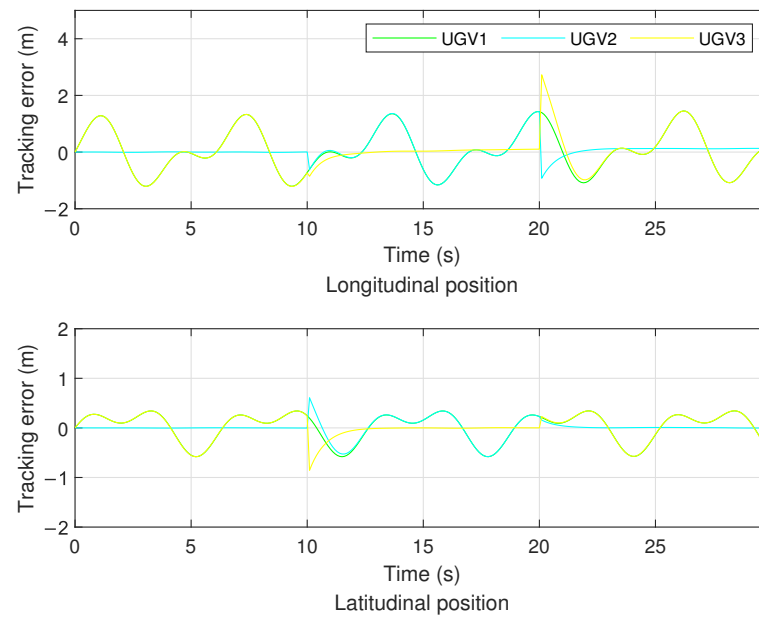


Figure 7. Position errors of tail-sitters (baseline controller).

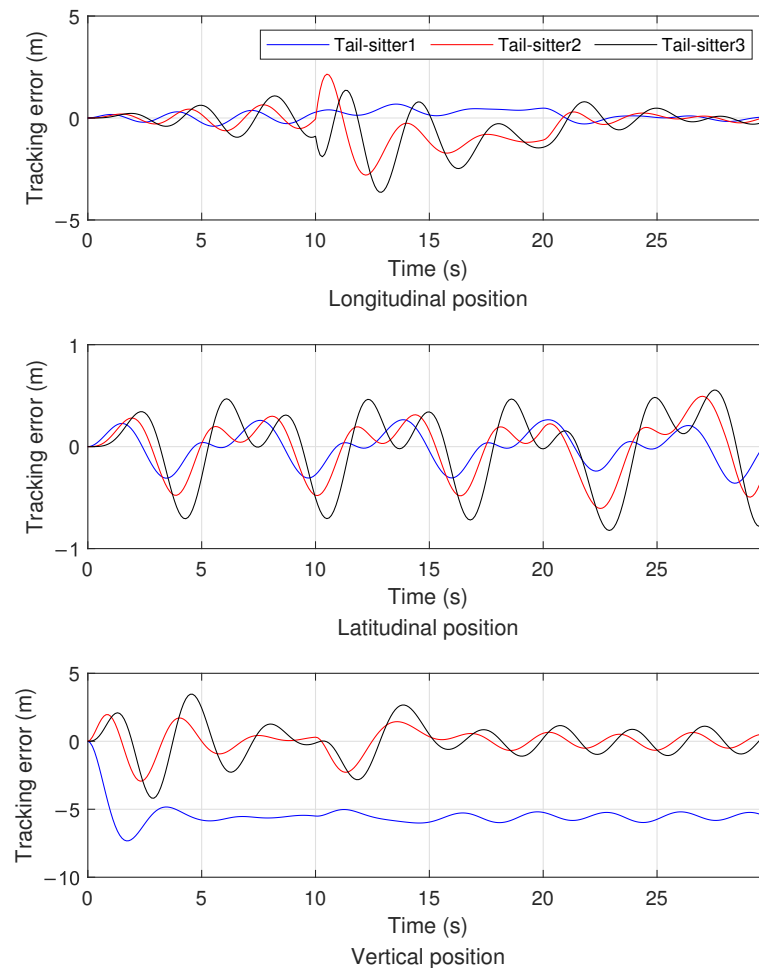


Figure 8. Position errors of UGVs (baseline controller).

To further verify the effectiveness of the proposed scheme, an additional set of simulation test with different disturbances and switching topology frequencies is given. The upper bound of parametric uncertainties is set to be 30% of its nominal. The exter-

nal disturbances are chosen as $F_{ig,1} = 2 \sin(3t) + 2 \cos(2t)$, $F_{ig,2} = \sin(2t) + 1.2 \cos(3t)$, $M_{ig,d} = 1.2 \sin(2t) + \cos(3t)$, and

$$F_{id} = \begin{bmatrix} 10 \sin(3t) + 15 \cos(2t) \\ 18 \sin(3t) + 20 \cos(2t) \\ 14 \sin(3t) + 21 \cos(2t) \end{bmatrix}, M_{id} = \begin{bmatrix} 10 \sin(2t) + 5 \cos(3t) \\ 15 \sin(2t) + 10 \cos(3t) \\ 15 \sin(2t) + 10 \cos(3t) \end{bmatrix}.$$

During the coordination mission, the graph among the heterogeneous vehicle group is described as $G_{\sigma(0)}$, $G_{\sigma(10)}$, $G_{\sigma(15)}$, $G_{\sigma(20)}$, and $G_{\sigma(25)}$. The weighted matrix $W_{\sigma(t)}$ can be described as

$$W_{\sigma(t)} = [\chi(t) - \chi(t-10)]W_1 + [\chi(t-10) - \chi(t-15)]W_2 + [\chi(t-15) - \chi(t-20)]W_3 + [\chi(t-20) - \chi(t-25)]W_1 + \chi(t-25)W_2.$$

The simulation results for the formation pattern using the designed formation controller are depicted in Figures 9 and 10. One can see that the coordination scenario for multiple tail-sitters and ground vehicles can be realized under switching topologies. All position errors rapidly converge within 3 s after each topology switching instant, and no obvious error divergence occurs even under 30% parameter uncertainty and large external disturbances. The proposed robust control algorithm attains enhanced path-tracking capability relative to the benchmark control law.

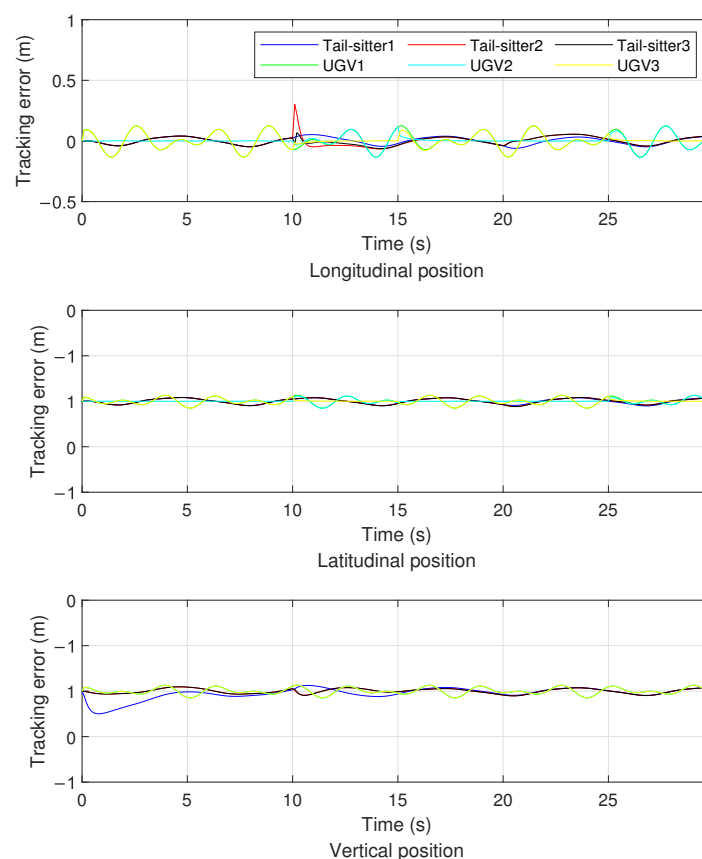


Figure 9. Position errors (proposed controller).

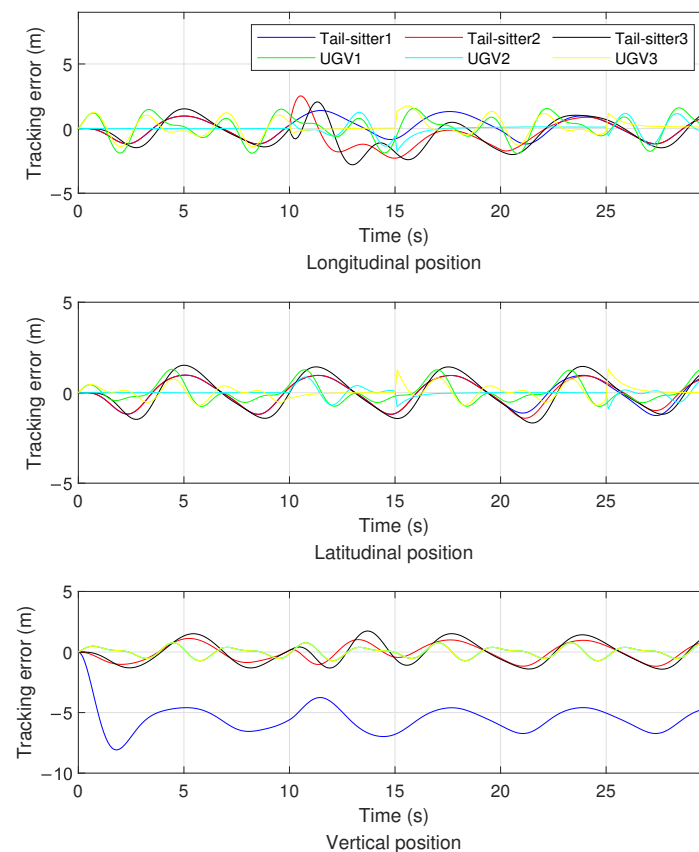


Figure 10. Position errors (baseline controller).

6. Conclusions

The coordination control problem is studied for a special heterogeneous system consisting of multiple tail-sitters and unmanned ground vehicles under switching topologies and uncertain communication links. A robust time-varying pinning cooperative scheme is developed to attain target collaborative behavior under model uncertainties and external interferences. The tracking errors of the air-ground system quickly converge to a small bounded region within predetermined finite intervals under switching topologies, parameter/link uncertainties, and disturbances. The effectiveness of the constructed robust time-varying pinning strategy is validated by simulation tests for multiple ground vehicles and tail-sitters.

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