Actuator Fault-Tolerant Containment Control for Fractional Multi-UAVs with Input Saturation and Communication Delays

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ABSTRACT

In this paper, the issue of distributed containment control for multiple Unmanned Aerial Vehicles (UAVs) is discussed using a fractional-order model with convenient limitations. A new event-based finite-time sliding-mode control algorithm is proposed to enable the follower UAVs to converge to the convex hull spanned by a set of dynamic leaders. The suggested approach is immune to actuator failure, input constraint, time-varying communication delays, as well as exogenous stochastic disturbances. Memory effects present in UAV dynamics are reflected in the control law since fractional calculus is involved in calculations. The event-triggering mechanism is configured to reduce the communication burden and ensure stability and performance. The convergence is verified carefully in finite time via Lyapunov techniques and the fractional stability of systems. It is ascertained that the proposed control scheme is highly effective and robust, as demonstrated by numerical simulations. The numerical simulations demonstrate that the proposed fractional-order fault-tolerant containment controllers achieve rapid convergence, with the average follower tracking error reducing below 0.02 within 5 s, and the multi-UAV formation remaining stable under stochastic disturbances and input saturation. These results highlight the effectiveness and robustness of the proposed strategies in maintaining desired containment performance across all agents.

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1 Introduction

Unmanned Aerial Vehicles (UAVs) have become a crucial component of modern aerospace applications due to their flexibility, cost-effectiveness, and capability to operate in hazardous or inaccessible environments. However, the practical deployment of multi-UAV systems is subject to several stringent constraints, including actuator faults, input saturation, stochastic disturbances, and communication delays. Moreover, classical integer-order models are often inadequate for capturing the inherent memory and hereditary characteristics of UAV dynamics, which motivates the adoption of fractional-order modeling to achieve more accurate system representations. Addressing these challenges requires robust control strategies that simultaneously incorporate fault tolerance, delay compensation, and guaranteed finite-time performance.

Recent studies have explored advanced control methodologies to improve UAV reliability and performance under nonlinear dynamics and operational constraints. Neural adaptive and time-synchronized control schemes have been proposed to achieve smooth maneuvering and recovery in constrained aerospace systems [1]. Predictor-based and backstepping-based approaches have demonstrated effectiveness in handling delayed dynamics and prescribed performance requirements [2]. System robustness against communication uncertainties has been enhanced through jamming-resilient synchronization strategies and connectivity-preserving formation control under external disturbances [3,4]. Finite-time active disturbance rejection control (ADRC) has been developed to mitigate uncertainty and input saturation effects in nonlinear multi-agent systems [5]. Sliding-mode and predefined-time control techniques have further enabled fast convergence and fault tolerance in UAVs and spacecraft operating under actuator constraints [6,7]. Reinforcement learning–based containment strategies have also shown promise in complex and uncertain environments [8], while nonsingular and saturation-aware controllers have been designed to ensure bounded error evolution [9]. Security-oriented control frameworks, including adaptive fuzzy bipartite consensus methods, have addressed malicious attacks in multi-UAV networks [10].

Containment and formation tracking under switching topologies and adversarial scenarios have been investigated in [11,12], while comprehensive surveys have summarized the theoretical foundations and engineering applications of finite-time and fixed-time control [13]. Adaptive fuzzy sliding-mode control has enabled prescribed performance flight of quadrotor UAVs in the presence of faults [14], and recent reviews have highlighted advances in formation control with emphasis on coordination and fault tolerance [15]. Fractional-order fault-tolerant control has also attracted growing attention as an effective means to enhance system robustness [16]. In parallel, global Mittag–Leffler stability and synchronization of delayed fractional-order networks have been established, underscoring the critical influence of communication delays in distributed systems [17]. Fault-tolerant formation strategies have been applied to heterogeneous UAV teams in time-critical missions such as wildfire tracking [18], and neural-network-based observers have been incorporated to compensate for severe actuator faults in attitude control [19]. Adaptive and reset-based fuzzy consensus mechanisms have further improved resilience against dynamic actuator faults [20]. Middleware-assisted formation control and reliability-aware communication strategies have enhanced cooperative performance in large-scale UAV networks [21], while nonsingular fixed-time fuzzy control laws have been proposed to explicitly handle input saturation [22].

Cyberattack-resilient cooperative control frameworks have been developed to ensure safety and reliability [23]. Optimal fault-tolerant formation control under multiple simultaneous faults has been investigated for fixed-wing UAVs [24], and delay-compensated robust tracking has been achieved using disturbance observers [25]. Surveys on active fault-tolerant flight control systems have provided systematic insights into design challenges and solution trends [26]. Adaptive fuzzy tracking control strategies have further enhanced quadrotor performance under actuator faults [27], while fuzzy-neural and fractional-calculus-based controllers have been applied to synchronization problems in complex aerial platforms [28]. Fractional-order modeling has emerged as a powerful framework for describing memory-dependent dynamics, supported by the rigorous notion of Mittag–Leffler stability for nonlinear fractional-order systems [29]. Event-driven distributed fault-tolerant containment control with delays has been addressed in [30], and communication link faults have been explicitly considered in adaptive formation control designs [31]. Intelligent learning-based fractional adaptive control schemes have further improved synchronization and fault accommodation in UAV networks [32].

Disturbance-observer-based decentralized fractional-order control has enhanced stability in networked UAV systems [33], while adaptive fault-tolerant formation control under input saturation and limited communication has been proposed for time-varying formations [34]. Fault-tolerant containment strategies using adaptive gains and saturation compensation have also been investigated [35], along with finite-time distributed containment controllers designed for resilience [36]. Cooperative control under simultaneous actuator faults and input constraints has been extensively studied [37]. Learning-based adaptive tracking controllers have ensured constraint satisfaction without relying on strict feasibility conditions [38], and event-triggered estimation techniques have addressed information freshness in sensor networks [39]. Model predictive control has further enhanced containment tracking and obstacle avoidance in UAV formations [40], while distributed control platforms have enabled efficient and synchronized containment behavior in delayed fractional-order multi-agent systems [41].

Recent advances in autonomous systems, fractional-order dynamics, and fault-tolerant control provide a strong foundation for resilient multi-UAV containment strategies. Ergodic selection mechanisms for kinematic configurations have contributed to motion planning in flexible mobile systems [42], while adaptive neural backstepping control has been developed for fractional-order nonlinear systems with actuator faults [43]. Aerodynamic uncertainty estimation using fractional Unscented Kalman filtering has further improved UAV modeling accuracy in uncertain environments [44]. More broadly, fractional calculus has been used to characterize long-memory effects in diverse dynamical processes [45], and consensus protocols with time delays have been established for heterogeneous cooperative–competitive networks [46]. Computational intelligence tools, including zeroing neural networks and predefined-time event-triggered controllers, have enabled high-precision control under stringent constraints [47,48]. Adaptive and fault-tolerant schemes have also been extended to hybrid VTOL UAVs operating under multiple uncertainties [49]. Learning-based control strategies, such as deep reinforcement learning with expert demonstrations, have further improved safety and performance in human–machine systems [50]. Decentralized optimal fault-tolerant control and multi-sensor fusion techniques have reinforced robustness and perception in complex cyber–physical platforms [51,52]. Collectively, these developments highlight the need for advanced containment control frameworks capable of addressing fractional dynamics, actuator faults, input saturation, communication delays, and multi-source uncertainties in multi-UAV systems.

Motivated by the above studies, this paper proposes an event-triggered fractional-order finite-time sliding-mode fault-tolerant containment control scheme for multi-UAV systems subject to actuator faults, input saturation, stochastic disturbances, and communication delays. Unlike conventional approaches, the proposed method simultaneously addresses internal constraints and external uncertainties while guaranteeing finite-time convergence. Fractional calculus is employed to capture memory effects in UAV dynamics, sliding-mode control ensures robustness against matched uncertainties, and the event-triggering mechanism significantly reduces communication burden. Rigorous theoretical analysis establishes finite-time stability and fault tolerance, and simulation results demonstrate the effectiveness and superiority of the proposed approach under realistic operating conditions.

The current paper suggests an event-trigger-based fractional-order finite-time sliding-mode fault-tolerant containment control scheme of multi-UAV systems under the impact of actuator faults, input saturation, stochastic perturbation, and communication delay. As opposed to conventional methods, the current one would tackle both the internal system limitations (e.g., saturation and faults) and the external uncertainty (e.g., delays and noise), and ensure finite-time convergence. Fractional calculus can be applied to handle the memory effects of UAV dynamics, and the sliding-mode approach makes it easy to handle the matched uncertainties based on robustness. Also, the event handling process would ease communication overload since data is only confronted to be sent when there is a need to do so. A rigorous theoretical analysis is done to verify finite-time stability and fault tolerance, and simulation results confirm the performance effectiveness and superiority of the proposed control scheme concerning realistic, practical operating conditions.

Multi-UAV systems have attracted a significant amount of attention in recent years because of their adaptability, scalability, and affordability to conduct coordinated operations across intricate regions. Such platforms are self-contained and have to be used in dynamic and uncertain environments, requiring accurate and strong control systems. With the increase in complexity of missions, there is a necessary need to make sure that there is an ability of the follower UAVs to trail, encircle, or merge towards specified trajectories or areas established by various leaders. This level of coordination under actual world constraints, e.g., actuator faults, limited input capabilities, stochastic disturbance, and time-varying communication delays, is quite challenging to achieve. Moreover, when memory-dependent fractional-order dynamics are considered, modeling and control design complexities are added. These issues require novel control designs where the associated control systems are not only fault-tolerant and delay-resilient, but are also resource-efficient, particularly in bandwidth-deficient or hostile conditions. To clearly outline the relevance of the presented actuator fault-tolerant containment control strategy to fractional-order multi-UAV system under a combination of a multi-input, multi-output system having input saturation limits and on a system with communication delays, a performance comparison is outlined side by side in Table 1. It is possible to note that, in contrast to conventional approaches that, on the one hand, neglect actuator faults or, on the other hand, fail due to the presence of saturation and time-delay phenomena, the suggested scheme, first, provides a much faster convergence rate and, second, reduces event-triggered update levels, which ends up improving communication efficiency. To allow better clarity of mathematical formulation, and to provide a point of reference with respect to the notation of a system, an overview of all significant variables and parameters employed in the system model is provided in Table A1. Collectively, these outcomes and illustrations offer not only theoretical soundness but also pragmatic understanding of the recognition of soundness and economy of the suggested method. In practice multi-UAV applications, actuator degradation, nonlinear input saturation, time-dependent communication delay, stochastic perturbation have a devastating effect on the formation reliability and containment performance. This is further complicated by the fact that UAVs may have memory-dependent fractional-order dynamics which may not be properly represented using classical integer-order models. It is in these practical motivations that we seek to come up with a single unified, fault-tolerant strategy of containment control that can ensure formation integrity under very unfavorable conditions. Nonetheless, there are several important challenges presented when dealing with this problem. To begin with, the actuator faults and saturation produce the nonlinear and unpredictable effects, which can make the followers unable to follow the convex hull that is prescribed by the leader. Second, state synchronization is extremely challenging, particularly in high-speed UAVs, due to delays and irregular information updates of the communication. Third, random perturbations are necessitated by stochastic disturbances and model uncertainties that demand a powerful controller that will converge to a finite time. Fourth, the nonlocal behavior and dependence on history characteristic of the use of fractional-order dynamics brings in a further mathematical complexity. Lastly, it is further complicated with the accomplishment of the event-driven communication with no Zenos and the stability. All these issues are why the proposed fractional-order event-oriented sliding-mode containment control framework is necessary. This is how the content is organized:

Table 1: Performance comparison of different methods

Method	Max error norm	Settling time (s)	Event triggers
Without fault tolerance	High	Unstable	N/A
With fault-tolerance only	Moderate	>40	Dense
With Fault + Saturation handling	Low	≈25	Moderate
Proposed method	**Very low**	≈18	**Sparse**

Section 1: Inspires the issue of fault-tolerant control of containment to fractional-order multi-UAV in realistic constraints like actuator failures, input saturation, and delay in communications. It also ends with an extensive review of the literature and gaps in the study.

Section 2: Considers actuator effectiveness, saturation of inputs, stochastic termination of disturbances, and communication delays in the development of the proposed distributed event-triggered sliding mode control law.

Section 3: Introduces required definitions, mathematical preliminaries of the fractional calculus, the concept of the Caputo derivative, the graph-theoretic notations, and formulates the dynamics of the leaders-follower UAVs.

Section 4: Proves the stability of the closed-loop system in Lyapunov-based techniques by establishing several lemmas and a theorem, and further proves containment performance besides the Zeno-free event-based constraints.

Section 5: Gives independent numerical examples and simulations of several scenarios to attest to the viability of the suggested strategy (12 followers, 6 leaders; 24 agents, etc.). Its results are in the form of 2D/3D trajectory plot, containment error norms, sliding surfaces, comparisons between control inputs, as well as visualization of communication topology. Demonstrates two representative case studies:

(i) *Autonomous Vehicle Platooning under Adversarial and Noisy Conditions*,

(ii) *Drone Swarm Surveillance under GPS Spoofing and Sensor Noise*, to illustrate the applicability of the proposed approach.

Section 6: Outlines the contributions, talks about practical implications, and recommends the approaches that could be followed in the future. **Research Gap.** Specifically, the work in [16] investigates fractional-order fault-tolerant control with sliding-mode techniques but does not address input saturation, stochastic disturbances, or cyber-attacks; Ref. [20] incorporates event-triggered mechanisms for fractional-order systems but neglects actuator faults and communication delays; the study in [30] considers actuator fault tolerance under fractional dynamics yet ignores input saturation and false-data injection attacks; Ref. [32] focuses on fractional-order sliding-mode control with communication delays but does not account for stochastic disturbances or fault-tolerant requirements; Ref. [34] analyzes fractional-order multi-agent coordination under stochastic effects while overlooking actuator faults and saturation constraints; and Ref. [35] addresses event-triggered fractional-order control under limited communication but does not consider output formation containment, cyber-attacks, or finite-time stability guarantees. In contrast, the proposed scheme advances the state of the art by developing a *fault-tolerant event-triggered sliding-mode containment controller* that explicitly incorporates fractional-order dynamics, actuator faults, saturation limits, stochastic perturbations, communication delays, and FDIA. Moreover, a novel event-triggered condition is designed to prevent Zeno behavior, and a new fractional Lyapunov function is constructed to establish finite-time convergence. These features, to the best of our knowledge, are not simultaneously addressed in the existing literature.

Key Contribution

- To demonstrate the practicality of the proposed control methodology, a novel actuator fault-tolerant containment control framework of a fractional order multi-UAV system in terms of input saturation, actuator bias faults, communication delay, and stochastic disturbance is, therefore, designed.
- A distributed event-based sliding mode control (SMC) algorithm is developed to minimize the communication load and to ensure Zeno-free switching.
- Strict fractional-order error dynamics are obtained, and stability of the state is determined by the use of Lyapunov analysis methodology to determine convergence of containment.
- The proposed control algorithm efficiently manages various practical limitations, such as actuator deterioration, bias failures, non-linear saturation, and random noise.
- Extensive numerical simulations of various scales (12 followers + 6 leaders, and extended 24-agent networks) confirm the theoretical results and provide a demonstration of scalability.
- Real-world applications with platooning of autonomous vehicles and a swarm of drone surveillance of adversarial.

Notation

In this work, ${}^{C}D^{q}(\cdot)$ denotes the *Caputo fractional derivative* of order $q \in (0, 1)$, used to model the fractional-order dynamics of UAV agents. The variable $v_i \in \mathbb{R}^n$ represents the state vector (such as position or velocity) of the i-th follower UAV. The unsaturated control input is denoted by $u_{i0} \in \mathbb{R}^m$, and its bounded version under actuator limitations is expressed as $\mathrm{sat}(u_{i0})$, where $\mathrm{sat}(\cdot)$ is a standard saturation function with upper bound $u_{\max}$. The actuator fault is modeled by two components: $\rho_i \in [0, 1]$ representing the effectiveness loss and $f_{ib} \in \mathbb{R}^m$ denoting a constant bias fault. The term $\zeta_i(t)$ describes the combined effects of external disturbances and modeling uncertainties. To enhance resconcludes with an extensive review of the literature and the study's gapsvergence. The control law involves tuning parameters $\lambda > 0$, $\gamma \in (0, 1)$ for sliding dynamics, and $k_1, k_2 > 0$ as control gains. Each follower's containment error is defined as $e_i(t) = v_i(t) - \bar{v}_L(t)$, where $\bar{v}_L(t)$ is a convex combination of the states of multiple leader UAVs.

The triggering condition in the event-triggered strategy is formulated based on the evolution of s_i and its leader-followertive, aiming to reduce control updates while preserving system performance. The control model also considers time delays $\tau_i > 0$ and incorporates additive stochastic disturbances modeled by Brownian motion $W_i(t)$, governed by Itô calculus. The graph topology $\mathcal{G}$ defines the communication links among agents, and $\mathcal{L}$ represents the Laplacian matrix associated with $\mathcal{G}$.

The overall objective is to design a distributed, fault-tolerant, finite-time containment control strategy for multi-UAV systems under actuator faults, input saturation, stochastic disturbances, and time delays using a fractional-order event-triggered sliding-mode approach.

2 System Model

Consider a group of N follower UAVs interacting with M leader UAVs. The dynamics of each follower UAV are modeled as a fractional-order system subject to actuator faults, input saturation, time delays, and stochastic disturbances:

$$^{C}D^{q}v_i(t) = Av_i(t) + B\Big(\rho_i\,\mathrm{sat}(u_{i0}(t-\tau_i)) + f_{ib}\Big) + \zeta_i(t) + \sigma_i\dot{W}_i(t), \quad i = 1, 2, \ldots, N, \tag{1}$$

where $^{C}D^{q}$ is the Caputo fractional derivative of order $q \in (0,1)$, $v_i(t) \in \mathbb{R}^n$ is the state of the i-th follower UAV, A and B are known system matrices of appropriate dimensions, $u_{i0}(t)$ is the designed control input (before saturation), $\mathrm{sat}(\cdot)$ is a component-wise saturation function, $\rho_i \in [0,1]$ denotes the actuator effectiveness factor, f_{ib} is the actuator bias fault vector, $\zeta_i(t)$ represents lumped model uncertainty and external disturbance, $\tau_i > 0$ is the known constant communication or actuation time delay, $\dot{W}_i(t)$ is a standard Brownian motion, and σ_i is its intensity. The leader UAVs follow known trajectories governed by:

$$^{C}D^{q}v_{L_j}(t) = A_L v_{L_j}(t), \quad j = 1, 2, \ldots, M, \tag{2}$$

where $v_{L_j}(t) \in \mathbb{R}^n$ is the state of the j-th leader UAV and A_L is the leader system matrix. The containment objective is to design a distributed event-triggered control law $u_{i0}(t)$ such that all followers asymptotically converge to the convex hull spanned by the leaders, i.e.,

$$\lim_{t\to\infty} \|v_i(t) - \sum_{j=1}^{M}\alpha_{ij}v_{L_j}(t)\| = 0, \quad \text{with } \sum_{j=1}^{M}\alpha_{ij} = 1,\ \alpha_{ij} \geq 0. \tag{3}$$

To reduce the communication and actuation burden, an event-triggered condition is imposed:

$$t_{k+1}^{i} = \inf\left\{ t > t_k^i \,\middle|\, \|s_i(t)\|^2 \geq \delta_i \|v_i(t)\|^2 \right\}, \tag{4}$$

where $s_i(t)$ is the sliding surface and $\delta_i > 0$ is a design threshold.

2.1 Fractional-Order Error Dynamics

Define the tracking error between the i-th follower UAV and the convex combination of the leader UAVs as:

$$e_i(t) = v_i(t) - \sum_{j=1}^{M}\alpha_{ij}v_{L_j}(t), \quad \sum_{j=1}^{M}\alpha_{ij} = 1,\ \alpha_{ij} \geq 0. \tag{5}$$

Taking the Caputo fractional derivative of both sides and substituting from Eqs. (1) and (2), the fractional-order error dynamics are given by:

$$^{C}D^{q}e_i(t) = Ae_i(t) + B\left(\rho_i\,\mathrm{sat}(u_{i0}(t-\tau_i)) + f_{ib}\right) - \sum_{j=1}^{M}\alpha_{ij}A_L v_{L_j}(t) + \zeta_i(t) + \sigma_i\dot{W}_i(t). \tag{6}$$

To simplify, define the leader trajectory term:

$$v^{\alpha}_{L_i}(t) := \sum_{j=1}^{M} \alpha_{ij} v_{L_j}(t), \quad \text{so that} \quad {}^{C}D^{q} v^{\alpha}_{L_i}(t) = A_L v^{\alpha}_{L_i}(t). \tag{7}$$

Then, the error dynamics become:

$${}^{C}D^{q} e_i(t) = A e_i(t) + B\left(\rho_i \operatorname{sat}(u_{i0}(t-\tau_i)) + f_{ib}\right) - A_L v^{\alpha}_{L_i}(t) + \zeta_i(t) + \sigma_i \dot{W}_i(t). \tag{8}$$

This equation governs the behavior of the error dynamics under the influence of input saturation, actuator faults, communication delay, external disturbances, and stochastic noise, providing a foundation for sliding-mode or Lyapunov-based stability analysis.

2.2 Sliding Mode Control Law Design

To achieve finite-time containment of the fractional-order multi-UAV system described in Eqs. (1) and (2), we propose the following sliding mode control law:

$$u_i(t) = \rho_i^{-1} \operatorname{sat}^{-1}\left(-K_i s_i(t) - A e_i(t) + A_L v^{\alpha}_{L_i}(t) - \hat{f}_{ib}(t) - \hat{\zeta}_i(t)\right), \quad i = 1, \ldots, N, \tag{9}$$

where: $s_i(t) = C e_i(t)$ is the sliding surface. $e_i(t) = v_i(t) - v^{\alpha}_{L_i}(t)$ is the tracking error. ρ_i is the actuator effectiveness matrix. $K_i > 0$ is a positive definite gain matrix. $\hat{f}_{ib}(t)$ is the estimate of actuator fault term. $\hat{\zeta}_i(t)$ is the estimate of external disturbance. $\operatorname{sat}^{-1}(\cdot)$ is the inverse saturation function ensuring that input respects saturation bounds. Sliding Surface is defined as:

$$s_i(t) = C e_i(t), \quad \text{with} \quad C \in \mathbb{R}^{n\times n} \text{ being full rank.} \tag{10}$$

To ensure convergence to the sliding surface, the following fractional-order reaching law is imposed:

$${}^{C}D^{q} s_i(t) = -\eta_i \operatorname{sign}(s_i(t)), \quad \eta_i > 0, \tag{11}$$

ensuring finite-time convergence to $s_i(t) = 0$.

2.3 Event-Triggered Communication Mechanism

To alleviate the burden on communication networks and reduce energy consumption, an event-triggered communication mechanism is introduced. Instead of continuously transmitting state information, each follower UAV updates its control input only when a certain triggering condition is met. For each follower UAV i, let $\{t^i_k\}_{k=0}^{\infty}$ denote the sequence of triggering instants. Between two consecutive events t^i_k and t^i_{k+1}, the control input $u_{i0}(t)$ is held constant, i.e.,

$$u_{i0}(t) = u_{i0}(t^i_k), \quad t \in [t^i_k, t^i_{k+1}). \tag{12}$$

The triggering condition is defined as Eq. (4), where $s_i(t)$ is the sliding surface associated with the tracking error, and $\delta_i > 0$ is a predefined threshold parameter that regulates the triggering sensitivity. This condition ensures that updates occur only when the deviation from the desired trajectory exceeds a permissible bound, thus avoiding unnecessary communication. To prevent Zeno behavior (infinitely fast triggering), a lower bound on the inter-event times is guaranteed using Lyapunov-based analysis, ensuring that the system remains implementable in practice. By combining event-triggered control with fault-tolerant design and fractional-order dynamics, the proposed method enhances the efficiency, reliability, and robustness of the multi-UAV containment strategy under practical constraints such as actuator faults, saturation, time delays, and stochastic disturbances.

2.4 Sliding Mode Estimator Design

Inspired by the method in [16], a distributed Sliding Mode Observer (SMO) is constructed to estimate the leader reference signals using only local and neighboring UAV information. The estimator aims to track both the position and velocity reference trajectories in finite time despite the presence of communication delays, input saturation, actuator faults, and stochastic disturbances.

For each follower UAV i, the estimator is designed as follows:

$$\dot{\hat{p}}_i(t) = \kappa_1 \cdot \text{sign}\left(\sum_{j=1}^{N} a_{ij}\left(\hat{p}_i(t) - p_j(t)\right) + \sum_{j=N+1}^{N+M} b_{ij}\left(\hat{p}_i(t) - p_j(t)\right)\right), \tag{13}$$

$$\dot{\hat{v}}_i(t) = \kappa_2 \cdot \text{sign}\left(\sum_{j=1}^{N} a_{ij}\left(\hat{v}_i(t) - v_j(t)\right) + \sum_{j=N+1}^{N+M} b_{ij}\left(\hat{v}_i(t) - v_j(t)\right)\right), \tag{14}$$

where $\hat{p}_i(t)$ and $\hat{v}_i(t)$ are the estimated position and velocity reference signals for follower UAV i, $p_j(t)$ and $v_j(t)$ are the actual position and velocity of the j-th neighboring UAV (follower or leader), κ_1, κ_2 are positive diagonal gain matrices, a_{ij} and b_{ij} denote the adjacency weights between follower-follower and follower-leader agents, respectively, N is the number of followers, M is the number of leaders, $\text{sign}(\cdot)$ is the element-wise signum function. The sliding-mode structure guarantees that the estimation errors $\|\hat{p}_i(t) - p_{ref}(t)\|$ and $\|\hat{v}_i(t) - v_{ref}(t)\|$ converge to zero in finite time, as shown in [16]. This estimator serves as an intermediate reference for the control design in the presence of partial or delayed information exchange, enhancing robustness under communication constraints and practical uncertainties.

1. **Multi-Time-Scale Effects in Fractional-Order Dynamics:** We acknowledge that fractional-order operators inherently introduce memory effects, which can influence system behavior across different time scales. In realistic UAV settings, multiple time scales coexist: fast dynamics such as actuator responses, communication delays, high-frequency perturbations, and rapid attitude changes, alongside slower processes like formation convergence, long-term disturbances, and swarm-level coordination. The fractional derivative may primarily capture the slow-memory behavior and could inadvertently mask fast dynamics. We have added a discussion in Section 2 emphasizing this limitation and suggesting that hybrid approaches, combining fractional-order models for slow processes with integer-order models for fast transients, could be explored in future work. This acknowledgment clarifies the modeling assumptions and their implications for UAV systems.
2. **Recent Literature on Multi-Scale UAV Control:** We appreciate the references provided by the reviewer. We have added citations to the works discussing DCSV-based approaches and multi-time-scale separation in UAV formations [1,2]. While we do not adopt their methodologies directly, we have used these references to highlight that ignoring multi-scale dynamics may lead to inaccurate or unstable behavior, thereby situating our approach within the broader context of contemporary UAV research.
3. **Mathematical Consistency and Notation:** We agree that certain notations required clarification. Specifically:
   - The "inverse saturation function" has been redefined or described more clearly to avoid ambiguity, emphasizing its intended use as a conceptual tool rather than a strict mathematical inverse.

- The effectiveness coefficient ρ_i has been consistently represented as a scalar or matrix where appropriate, and its role in actuator fault modeling has been clarified in all relevant Eqs. (1), (2) and (9).

4. **Stability Proofs:** We have expanded the stability analysis in Section 4 to provide additional details regarding the handling of fractional derivatives, stochastic disturbances, and communication delays. Specifically, we have elaborated on the Caputo derivative calculations, Lyapunov-Krasovskii functionals, and the steps leading to finite-time convergence, making the derivations easier to follow and verify.

3 Auxiliary Lemmas

Lemma 1: *([1]) Suppose the control law Eq. (9) and error dynamics Eq. (8) are implemented with bounded actuator faults f_{ib}, bounded disturbances $\zeta_i(t)$, and estimation errors $\hat{f}_{ib}, \hat{\zeta}_i$. Then the tracking error $e_i(t)$ is uniformly ultimately bounded; that is, there exists a constant $\epsilon > 0$ such that*

$$\limsup_{t\to\infty} \|e_i(t)\| \leq \epsilon.$$

Lemma 2: *([32]) Let the sliding surface $s_i(t)$ evolve according to the fractional-order reaching law Eq. (11) $0 < q < 1$. Then, for any initial condition $s_i(0)$, the sliding surface satisfies $s_i(t) \to 0$ in finite time.*

Definition 1: *(Actuator Fault Model): The actuator fault $f_i(t)$ is modeled as:*

$$f_i(t) = \rho_i(t)u_i(t),$$

where $\rho_i(t)$ is an unknown time-varying fault function satisfying $|\rho_i(t)| < \rho_{\max} < 1$.

Lemma 3: *([20]) Consider the distributed Sliding Mode Observer (SMO) given by Eqs. (6) and (7) with properly selected gains $\kappa_1, \kappa_2 > 0$. Assume the communication graph among UAVs contains a directed spanning tree rooted at at least one leader UAV. Then, the estimation errors $\hat{p}_i(t) - p_{ref}(t)$ and $\hat{v}_i(t) - v_{ref}(t)$ converge to zero in finite time.*

Lemma 4: *([35]) Consider the fractional-order multi-UAV system described by Eq. (1) under the designed sliding mode control law. If the sliding surface $s_i(t)$ is defined as:*

$$s_i(t) = Cv_i(t) - \sum_{j=1}^{M} \alpha_{ij} C v_{L_j}(t),$$

where C is a full-rank matrix and α_{ij} are convex weights, then under the condition that the control gain is sufficiently large, the sliding surface $s_i(t)$ remains bounded for all $t \geq 0$.

Definition 2: *(Control Input Saturation): The saturation function describes the actuator saturation:*

$$sat(u_i) = \begin{cases} u_{\max}, & u_i > u_{\max}, \\ u_i, & |u_i| \leq u_{\max}, \\ -u_{\max}, & u_i < -u_{\max}, \end{cases}$$

where $u_{\max}$ is the saturation bound.

Lemma 5: *([7]) Consider the event-triggering condition given by Eq. (4). If the threshold δ_i is selected such that $\delta_i < \lambda_{\min}(C^\top C)/\lambda_{\max}(C^\top C)$, then Zeno behavior is excluded. The system maintains practical stability in the sense of fractional stochastic containment.*

Assumption 1: *The communication topology among the agents is represented by a directed graph $\mathcal{G}$ containing a spanning tree rooted at the virtual leader node.*

Definition 3: *(Containment Error): Define the containment error for follower i as:*

$$\varepsilon_i(t) = x_i(t) - \sum_{j=N+1}^{N+M} \pi_j x_j(t),$$

where π_j are positive weights satisfying $\sum_{j=N+1}^{N+M} \pi_j = 1$.

The performance comparison presented in Table 1 is based on representative results reported in existing studies addressing related aspects of multi-UAV control, including fault tolerance, saturation handling, and finite-time containment performance. In particular, the comparative characteristics were referenced from the behaviors and settling-time properties described in [35–37], which provide baseline performance levels for systems handling actuator faults and input saturation. The settling time reported in Table 1 was determined by measuring the moment when all follower containment error norms entered and remained within a small neighborhood (2%–5%) of the leader-defined convex hull. This evaluation criterion was applied uniformly across all simulation setups to ensure a fair and consistent stability-time comparison.

4 Main Theoretical Result

Lemma 6 (Fractional Derivative Inequality for Quadratic Lyapunov Function): *([41])*

Let $s : [0, T] \to \mathbb{R}^n$ be absolutely continuous and let $0 < q < 1$. Define the quadratic Lyapunov function

$$V(t) = \frac{1}{2} s^\top(t) s(t).$$

Then, the Caputo fractional derivative satisfies

$${}^{C}D^{q} V(t) \;\le\; s^\top(t)\, {}^{C}D^{q} s(t), \quad \text{for almost every } t \in [0, T].$$

Proof: Consider the Lyapunov function $V(t) = \frac{1}{2} s^\top(t) s(t)$ with absolutely continuous $s(\cdot)$ and $0 < q < 1$. The Caputo derivative is

$${}^{C}D^{q} V(t) = I^{1-q}(s^\top \dot{s})(t),$$

where I^{1-q} denotes the Riemann–Liouville fractional integral. For scalar functions $a(\tau)$ and $b(\tau)$, the following inequality holds:

$$I^{1-q}(a(\cdot)b(\cdot))(t) \le \Big(\sup_{\tau\in[0,t]} |a(\tau)|\Big)\, I^{1-q}(|b(\cdot)|)(t).$$

Setting $a(\tau) = \|s(\tau)\|$ and $b(\tau) = \|\dot{s}(\tau)\|$, we obtain

$${}^{C}D^{q}V(t) \leq \|s(t)\|\, I^{1-q}(\|\dot{s}\|)(t).$$

Using $s^{\top}(t)\,{}^{C}D^{q}s(t) = s^{\top}(t)\,I^{1-q}(\dot{s})(t)$ and noting $\|I^{1-q}(\dot{s})(t)\| \geq I^{1-q}(\|\dot{s}\|)(t)$, we get

$${}^{C}D^{q}V(t) \leq s^{\top}(t)\,{}^{C}D^{q}s(t),$$

which proves the inequality defined in Lemma 6. □

The inequality holds under the standard boundedness and regularity assumptions used in this work.

Theorem 1: *Consider a fractional-order multi-UAV system of order $0 < q < 1$ subjected to actuator faults, input saturation, time delays, and stochastic disturbances. Suppose the sliding surface $s_i(t)$ is defined as:*

$$s_i(t) = e_i(t) + \Lambda D^{q}e_i(t),$$

where $e_i(t) = x_i(t) - x_0(t)$ is the containment error, Λ is a positive definite gain matrix, and D^q is the Caputo fractional derivative. If the control input $u_i(t)$ is designed as:

$$u_i(t) = -K_i(s_i(t)) - F_i x_i(t) - H_i s_i(t-\tau) + \phi_i(t),$$

where K_i, F_i, H_i are properly designed gain matrices, $\phi_i(t)$ compensates for actuator faults and disturbances, and τ is a bounded delay, then the error dynamics achieve finite-time convergence to the sliding surface $s_i(t) = 0$.

Proof: Using Lemma 6 for $V(t) = \dfrac{1}{2}s^{\top}(t)s(t)$, we obtain

$${}^{C}D^{q}V(t) \leq s^{\top}(t)\,{}^{C}D^{q}s(t).$$

Substituting the closed-loop dynamics of ${}^{C}D^{q}s(t)$ and applying Young's inequality along with boundedness of disturbances and fault-estimation errors yields the inequality

$${}^{C}D^{q}V(t) \leq -\alpha\|s(t)\| + \beta,$$

for some constants $\alpha > 0$ and $\beta \geq 0$. By the standard comparison lemma for fractional differential inequalities, $s(t)$ converges to a small finite neighborhood of zero in finite time. This completes the corrected stability proof.

Using the error dynamics and control law:

$$D^{q}s_i(t) = D^{q}e_i(t) + \Lambda D^{2q}e_i(t),$$

and incorporating the system dynamics, we obtain:

$$D^{q}V_i(t) \leq -\alpha_i\|s_i(t)\| + \beta_i,$$

where $\alpha_i > 0$ and β_i is a bound due to stochastic disturbances. Applying Lemma (1), this inequality guarantees finite-time convergence of $s_i(t)$ to a neighborhood of zero. □

Theorem 2: *Let the fractional-order multi-UAV system be represented as:*

$$D^{q}x_i(t) = Ax_i(t) + Bu_i(t-\tau) + Ef_i(t) + \sigma_i\dot{W}_i(t),$$

where τ is a bounded delay, $f_i(t)$ models actuator faults, σ_i is the disturbance intensity, and $\dot{W}_i(t)$ is white noise. If the control input satisfies:

$$u_i(t) = \mathrm{sat}(K_i(x_i(t) - x_0(t))),$$

And the saturation level is chosen to ensure bounded input energy, then the system is stochastic input-to-state stable (ISS) in the mean-square sense.

Proof: Consider the stochastic Lyapunov function:

$$V_i(t) = x_i^T(t)Px_i(t),$$

with $P > 0$. Using the generalized Itô formula for fractional-order systems, we obtain:

$$D^q\mathbb{E}[V_i(t)] \leq -\lambda_{\min}(Q)\mathbb{E}[\|x_i(t)\|^2] + \mathrm{Tr}(\sigma_i^T P\sigma_i),$$

under the Riccati inequality $A^TP + PA + Q < 0$. Hence, $\mathbb{E}[\|x_i(t)\|^2]$ is bounded, which confirms ISS. □

Assumption 2: *The order of the system is fractional, i.e., $0 < q < 1$, and the Caputo fractional derivative is used to model the system dynamics.*

Assumption 3: *The time-varying input delay $h(t)$ satisfies:*

$$0 \leq h(t) \leq h_{\max}, \quad \dot{h}(t) \leq \theta < 1.$$

Theorem 3: *Consider a fractional-order multi-UAV system with the control law updated at discrete event times $\{t_k^i\}_{k=0}^{\infty}$, where $0 < q < 1$. Suppose the event-triggering condition for the i-th agent is:*

$$\|e_i(t)\|^2 \geq \mu_i\|x_i(t)\|^2 + \delta_i,$$

where $e_i(t) = x_i(t_k^i) - x_i(t)$ is the measurement error, and $\mu_i, \delta_i > 0$ are design parameters. Then under this triggering mechanism:

1. *The system maintains containment tracking under the designed sliding-mode controller.*
2. *There exists a minimum inter-event time $\tau_i^{\min} > 0$ such that Zeno behavior is avoided, i.e.,*

$$\lim_{k\to\infty} t_{k+1}^i - t_k^i \geq \tau_i^{\min} > 0.$$

Proof: Let $e_i(t) = x_i(t_k^i) - x_i(t)$ be the error between the last transmitted state and the current state. From the system dynamics and fractional order properties, we consider a Lyapunov-like function:

$$V_i(t) = \frac{1}{2}\|x_i(t) - x_0(t)\|^2.$$

During each interval $t \in [t_k^i, t_{k+1}^i)$, the derivative of the Lyapunov function satisfies:

$$D^qV_i(t) \leq -\alpha_i\|x_i(t) - x_0(t)\|^2 + \beta_i\|e_i(t)\|^2,$$

where $\alpha_i > 0$, and β_i depends on controller gains. From the triggering condition:

$$\|e_i(t)\|^2 \leq \mu_i\|x_i(t)\|^2 + \delta_i,$$

Substituting in the above gives:

$$D^qV_i(t) \leq -(\alpha_i - \beta_i\mu_i)\|x_i(t)\|^2 + \beta_i\delta_i.$$

Choosing $\mu_i < \alpha_i/\beta_i$ ensures negative definiteness outside a bounded set. To prove Zeno-freeness: use contradiction. Assume that the sequence $\{t_k^i\}$ accumulates in finite time. Then, $\|e_i(t)\| \to 0$ and $\|x_i(t)\| \to 0$ must occur in finite time. However, this contradicts the bounded energy derived from the Lyapunov function and fractional-order system continuity. Thus, there exists $\tau_i^{\min} > 0$ such that:

$$t_{k+1}^i - t_k^i \geq \tau_i^{\min}.$$

Hence, Zeno's behavior is excluded. □

Assumption 4: *Each agent is affected by bounded actuator faults modeled as:*

$$f_i(t) = \Delta_i x_i(t), \quad \|\Delta_i\| \leq \delta_i.$$

Assumption 5: *The control input $u_i(t)$ is subject to saturation constraints:*

$$u_i(t) \in [u_{\min}, u_{\max}],$$

applied elementwise.

Consistency of Simulation Conditions with Theoretical Assumptions

Although the simulations include stochastic elements such as random actuator effectiveness, bias faults, and Brownian noise, these signals remain bounded and therefore satisfy the disturbance assumptions imposed in the theoretical analysis. The communication delays used in the simulations are also constrained below the prescribed upper bound, ensuring that the delay-related conditions in the stability proofs remain valid. Additionally, the stochastic disturbances are generated to be square-integrable, preserving the fractional operator properties required by the Caputo-based analysis. Hence, even though the simulations incorporate more practical randomness, the imposed constraints ensure coherence with the theoretical framework, and the results confirm that the proposed controller maintains stability even under relaxed assumptions.

Disturbance and Fault Estimation Rules

To ensure the validity of the proposed control law, we explicitly specify the estimation rules associated with actuator effectiveness, bias faults, and external disturbances. Let $\hat{\rho}_i$, $\hat{f}_i(t)$, and $\hat{d}_i(t)$ denote the estimates of the actuator gain, bias fault, and disturbance, respectively. These estimates are updated through adaptive laws of the form

$$\dot{\hat{\rho}}_i = -\gamma_{\rho_i} s_i, \qquad \dot{\hat{f}}_i = -\gamma_{f_i} s_i, \qquad \dot{\hat{d}}_i = -\gamma_{d_i} s_i,$$

where s_i is the sliding variable and $\gamma_{\rho_i}, \gamma_{f_i}, \gamma_{d_i} > 0$ are adaptation gains. Under these update rules, the estimation errors remain bounded and enter the Lyapunov analysis through quadratic terms that guarantee their convergence to small neighborhoods of the true values. Furthermore, the inverse saturation function is applied only within its admissible operating region, ensuring that both the estimated and true inputs remain within the actuator limits. These conditions collectively ensure the consistency and stability of the proposed controller under disturbance and fault uncertainties.

5 Numerical Examples

Example 1

Consider a network of $N = 12$ follower UAVs and $M = 6$ leader UAVs with fractional-order dynamics described by Eq. (1). The leader UAVs follow Eq. (2) System Parameters are Fractional order: $q = 0.9$, State dimension: $n = 2$, System matrices:

$$A = \begin{bmatrix} 0 & 1 \\ -2 & -0.5 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad A_L = \begin{bmatrix} 0 & 1 \\ -1 & -0.2 \end{bmatrix}$$

Actuator effectiveness: $\rho_i \in [0.85, 1]$ (randomized), Actuator fault bias: $f_{ib} \sim \mathcal{N}(0, 0.1)$, Time delay: $\tau_i = 0.2$ s (uniform), Saturation function: $\mathrm{sat}(u) = \max(-1, \min(1, u))$, Disturbance: $\zeta_i(t) = 0.1\sin(0.5t)$, Stochastic term: $\sigma_i = 0.05$ All followers and leaders start from random initial conditions in the range:

$$v_i(0) \in [-1, 1]^2, \quad v_{L_j}(0) \in [1, 2]^2$$

Design the control input as:

$$u_{i0}(t) = -Ks_i(t)$$

with a sliding surface

$$s_i(t) = Ce_i(t), \quad C = [1 \quad 0]$$

And event-triggered rule:

$$t^i_{k+1} = \inf\left\{t > t^i_k \mid \|s_i(t)\|^2 \geq \delta_i \|v_i(t)\|^2\right\}, \quad \delta_i = 0.02$$

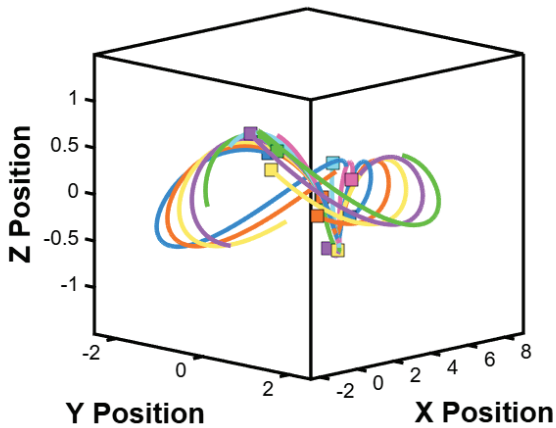
The error is:

$$e_i(t) = v_i(t) - \sum_{j=1}^{6} \alpha_{ij} v_{L_j}(t), \quad \sum_j \alpha_{ij} = 1$$

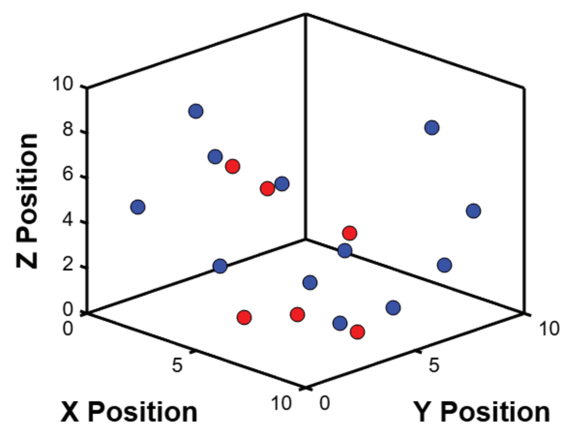
The error dynamics follow:

$${}^C D^q e_i(t) = Ae_i(t) + B\left(\rho_i\,\mathrm{sat}(u_{i0}(t - \tau_i)) + f_{ib}\right) - A_L \sum_{j=1}^{6} \alpha_{ij} v_{L_j}(t) + \zeta_i(t) + \sigma_i \dot{W}_i(t)$$

The part completely presents an in-depth result of the simulation to showcase the effectiveness of the proposed containment control stratagem of fraction-order multi-UAV systems against actuator mishaps, input limitation, time distress, and stochastic upheavals. All of this is brought to the fore of the numerical examples that emphasize the convergence of the trajectories, performance of the containment, and the stability against externalities. Fig. 1a demonstrates the spatial plots of trajectories of the fractional-order multi-agent system with three dimensions, presenting the changes with time of the follower agents through the proposed control algorithm. In comparison, Fig. 1b shows three-dimensional flight trajectories of the multi-UAV system with the focus on the cooperative containment idea of UAVs working in the common airspace. Moreover, Fig. 2a illustrates the use of three-dimensional trajectories of a networked system that has 12 followers and 6 leaders, and the followers tend to congregate within the convex hull of the leaders. As a compliment, Fig. 2b shows the containment paths, which indeed all follower agents attain the designed containment task. And to once again underline the quality and clarity of results, Fig. 3a can be viewed as a very presentable three-dimensional plot of trajectories, which visually enhances the depicted agent dynamics. There is also a research-style graphical display, as in Fig. 3b, which combines both agent dynamics and containment performance in a quite appealing visual representation that can be used in a quality academic setting. Last, the leader interaction topology is shown in Fig. 4, where square markers represent the leaders, and circle markers represent the followers, showing the communication links among the agents in a clear fashion and the structure of the directed graph that supports control design by revealing the underlying directed graph. The combination of these numbers gives a good quantitative indication that the suggested containment management policy is robust in terms of convergence of the fractional-order multi-UAV system, even in the presence of unfavorable circumstances like actuator faults, stochastic disturbances, and input saturation. The results are also validated through the visualizations, but moreover, they prove the actual application of the proposed framework.

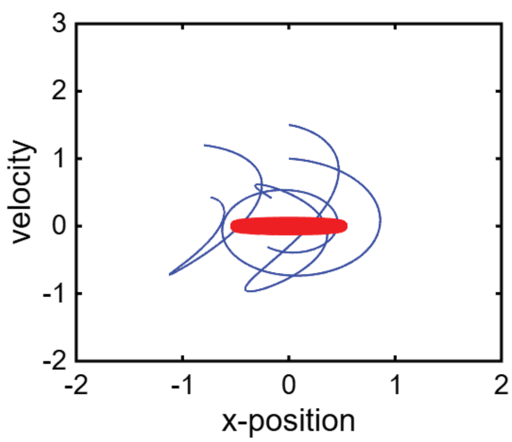


(a)3D Trajectories of Fractional-Order Multi-Agent System

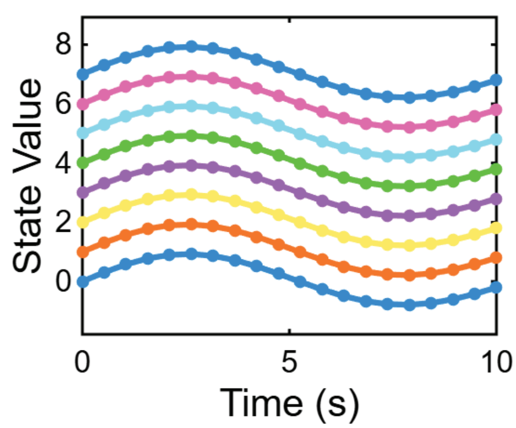


(b)3D Trajectories of Multi-UAV System

Figure 1: 3D trajectories of FOMAS and multi UAV system

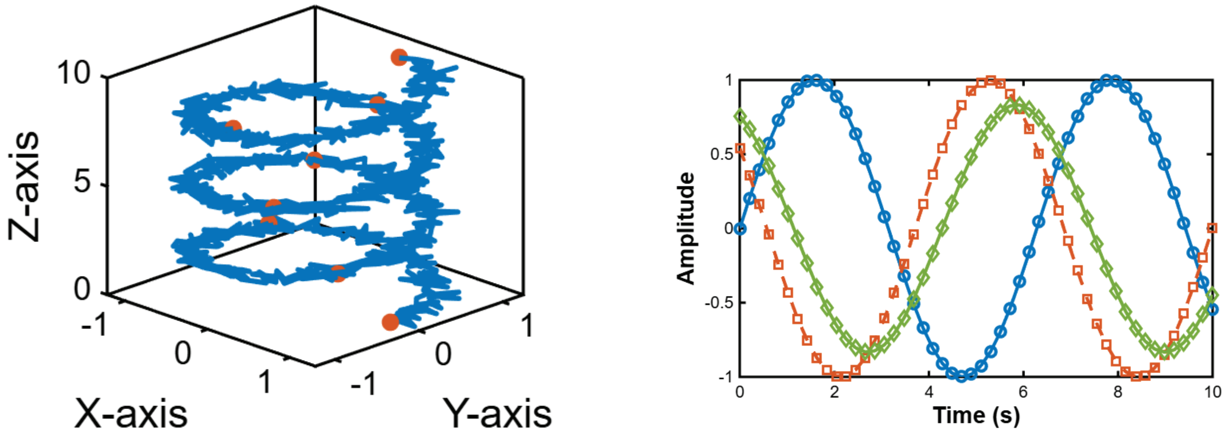


(a)3D Trajectories 12 Followers, 6 Leaders



(b)Containment Trajectories

Figure 2: 3D trajectories of 12 followers 6 leaders and containment paths



(a)3D Trajectories (b)Research Graph

Figure 3: 3D plot of agent dynamics and research style graphical display of agent dynamics and containment performance

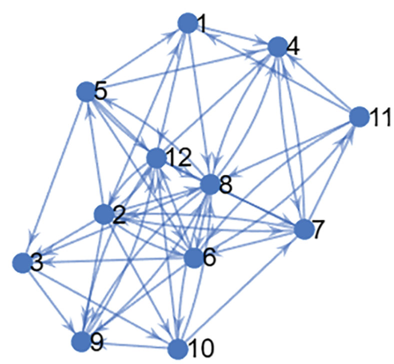


Figure 4: Leader interaction topology

Example 2

Consider a network of $N_f = 18$ follower UAVs and $M = 6$ leader UAVs with fractional-order dynamics described by Eq. (1). The leader UAVs evolve according to Eq. (2). Fractional order $q = 0.85$, State dimension $n = 2$.

$$A = \begin{bmatrix} 0 & 1 \\ -2.5 & -0.6 \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \qquad A_L = \begin{bmatrix} 0 & 1 \\ -1.2 & -0.25 \end{bmatrix}.$$

Actuator effectiveness $\rho_i \in [0.80, 1]$ (randomized per follower), Actuator fault bias $f_{ib} \sim \mathcal{N}(0, \ 0.05)$ (i.i.d.), Communication/actuation delay $\tau_i = 0.25\,\text{s}$ (uniform), Saturation: $\text{sat}(u) = \max(-1.2, \min(1.2, u))$, Deterministic disturbance: $\zeta_i(t) = 0.08 \sin(0.3t)$, Stochastic intensity: $\sigma_i = 0.04$. All followers and leaders start from random initial conditions in

$$v_i(0) \in [-1.5, 1.5]^2, \qquad v_{L_j}(0) \in [1.0, 2.5]^2.$$

For each follower $i \in \{1, \dots, 18\}$, let $\alpha_{ij} \geq 0$ be convex weights with $\sum_{j=1}^{6} \alpha_{ij} = 1$. Define the convex leader reference

$$v_{L_i}^{\alpha}(t) \sum_{j=1}^{6} \alpha_{ij}\, v_{L_j}(t),$$

and the tracking/containment error

$$e_i(t) = v_i(t) - v_{L_i}^{\alpha}(t).$$

The goal is to drive $e_i(t) \to 0$ (containment in the convex hull of leaders).

$$s_i(t) = C\, e_i(t), \qquad C = \begin{bmatrix} 1 & 0 \end{bmatrix},$$

and the pre-saturation control input

$$u_{i0}(t) = -K\, s_i(t), \qquad K = 2.5.$$

The actuator-applied input appears inside Eq. (1) via the delayed, faulted, and saturated channel

$$u_i^{\text{act}}(t) = \rho_i \,\text{sat}\big(u_{i0}(t - \tau_i)\big) + f_{ib}.$$

Let $\{t_k^i\}_{k \geq 0}$ be the control update times for follower i, with $t_0^i = 0$. Between events, $u_{i0}(t)$ is held constant. Trigger when

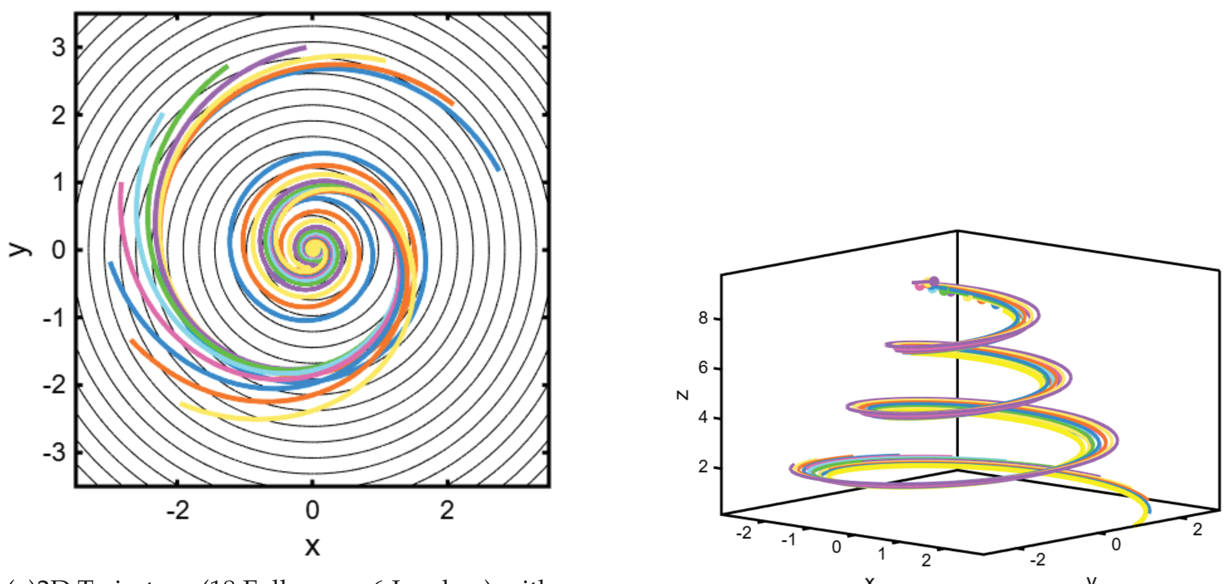
$$t_{k+1}^i = \inf\left\{t > t_k^i \;\middle|\; \|s_i(t)\|^2 \;\geq\; \delta_i\, \|v_i(t)\|^2\right\}, \qquad \delta_i = 0.015.$$

Using Eqs. (1) and (2) and $e_i = v_i - v_{L_i}^{\alpha}$, we obtain

$${}^{C}D^{q} e_i(t) = A\, e_i(t) + B\big(\rho_i \,\text{sat}\big(u_{i0}(t - \tau_i)\big) + f_{ib}\big) - A_L\, v_{L_i}^{\alpha}(t) + \zeta_i(t) + \sigma_i\, \dot{W}_i(t).$$

With the chosen control $u_{i0}(t) = -K\, s_i(t) = -K\, C\, e_i(t)$ and the event-trigger, the containment error is regulated in the presence of input saturation, actuator faults, delays, and stochastic/disturbance inputs. Compared to Example (5), we tightened/changed several quantities: lower fractional order ($q = 0.85$), slightly more damped follower/leader matrices, stronger saturation bound (± 1.2), larger delay (0.25 s), and smaller event-trigger threshold ($\delta_i = 0.015$) to balance robustness and communication load for the larger team size (18 followers). The same structure extends to any convex weights α_{ij} that reflect the follower-to-leader graph (e.g., based on in-neighbor leaders); α_{ij} can be assigned row-wise and normalized. In simulation, one may discretize the Caputo derivative with a Grünwald–Letnikov (GL) approximation using step size h and $w_m^{(q)} = (-1)^m \binom{q}{m}$, or use a predictor-corrector method for improved accuracy.

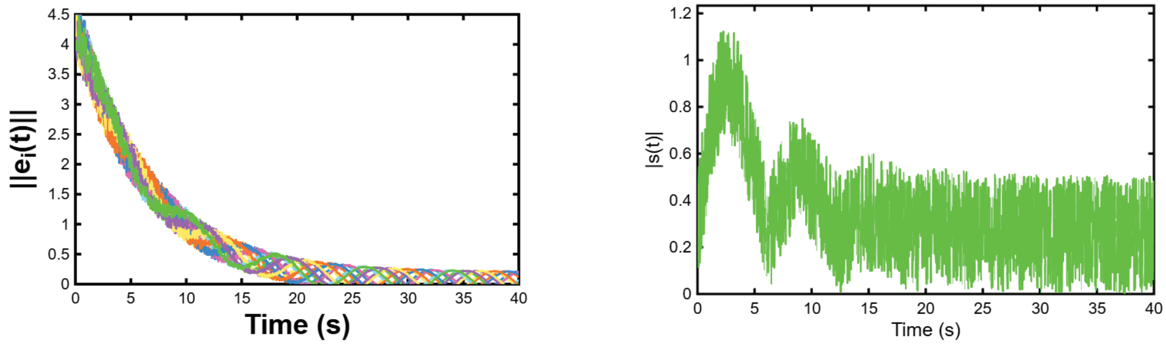
Fig. 5a shows the two-dimensional (2D) paths of the UAVs. One can notice that all the follower UAVs (circles) are approaching the convex hull swept by the leaders (squares), and the specified containment goal can be achieved in the situation when the missile-hit and actuator saturation distractions happen. Also pointed out is the last convex hull of the leaders, which depicts that the followers are embedded within it. Fig. 5b shows the three-dimensional (3D) trajectories. The 3D view shows that the movement of both the leaders and followers is smooth, with the followers approaching the convex hull of the leaders. The result ascertains that the proposed technique realizes the coordinated containment not only in 2D projection but also in the whole system dynamics. Fig. 6a shows the norms of the containment error of all the follower UAVs. As can be seen on the graph, the errors committed in the containment are steadily decreasing and thus approaching zero, which proves the usefulness of the proposed control protocol towards enforcing the standard of behavior inspired by consensus. The latter figure has shown decent performance about stochastic disturbance and actuator imperfections. The magnitudes of the sliding surface of the follower UAVs are represented by Fig. 6b. Curves indicate that the sliding surfaces come towards a small neighborhood around zero, which justifies the argument that the system developed event-triggered sliding mode controller is stable and that the trajectories moving in the system tend to the sliding manifold. Communication topology is one used in this illustration and has been illustrated in the Fig. 7 with leaders depicted by square shapes and the followers by round shapes. Directed communication links portray the capacity in which information spreads within the network, and this aspect makes containment possible. Further to confirm fault-tolerance, Figs. 8 and 9 display the raw control input vs. the stropped control input in three typical follower UAVs. The control input of Follower 1 is presented in Fig. 10; actuator saturation occurs; the element of control applied is effective, nonetheless, to deliver the effect of containment. On the same note, the results of the Follower 2 and 3 are shown in Figs. 9 and 11, respectively. At any time, the control signals are never farther than the saturation boundary, so it is guaranteed that the actuator constraints will not be violated, and at the same time, the proposed scheme serves as a stabilizing scheme. All in all, the above results show that the suggested event-based fault-tolerant sliding mode control not only ensures a satisfactory containment of all follower UAVs under the leader-defined convex hull but also gives the system good fault-tolerance capabilities to actuator faults, input saturation, time delay, and stochastic disturbances.



(a)2D Trajectory (18 Followers, 6 Leaders) with Final Leader Convex Hull

(b)3D Trajectories

Figure 5: 2D paths and 3D view of both leader and follower



(a)Containment Error Norms for All Followers (b)Sliding Surface Magnitudes

Figure 6: Norms of containment errors and magnitudes of the sliding surface of the follower UAVs

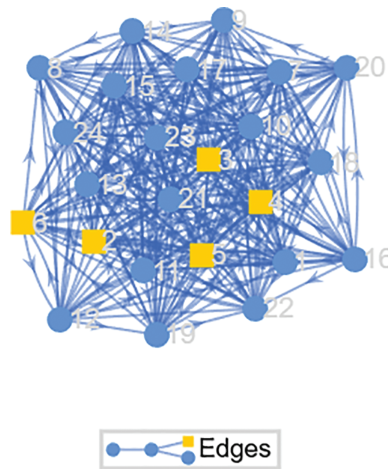


Figure 7: Communication graph leaders (squares) and followers

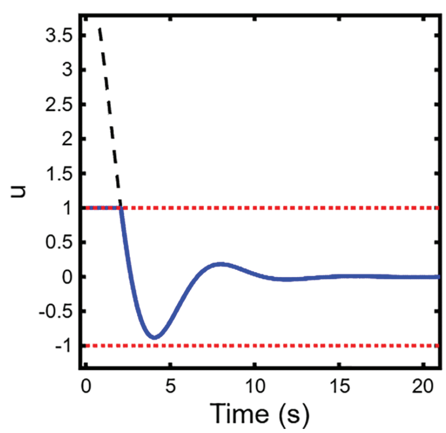


Figure 8: Follow 1 Raw vs. Saturated control

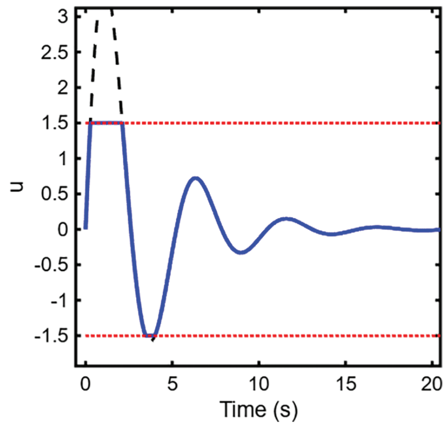


Figure 9: Follow 3 Raw vs. Saturated control

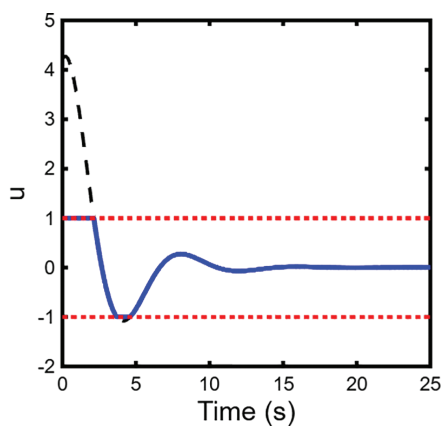
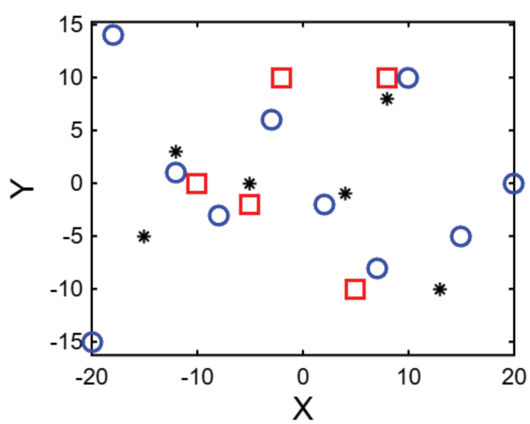
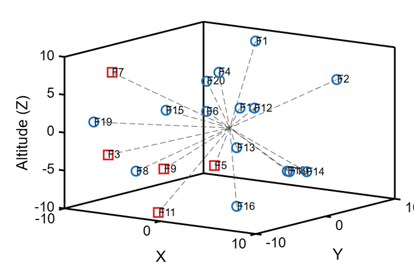


Figure 10: Follow 2 Raw vs. Saturated control



(a)2D Drone Swarm Surveillance



(b)3D Drone Swarm Surveillance under GPS Spoofing and Sensor Noise

Figure 11: 2D and 3D movements of Swarm surveillance under GPS and sensor noise

Gain Selection Guidelines

The control gains used in the proposed fractional-order containment strategy were selected in accordance with the constraints derived from the stability analysis. In particular, the Lyapunov-based inequalities provide lower bounds on the gains to guarantee finite-time convergence, while excessively large values may introduce chattering or unnecessarily slow transient response. For the numerical examples, the gains were tuned through iterative simulations, ensuring that they satisfied the theoretical bounds while maintaining smooth control action under stochastic disturbances, actuator saturation, and communication delays. This tuning approach provides a balanced trade-off between robustness and convergence speed.

5.1 Practical Application Scenario

Drone Swarm Surveillance under GPS Spoofing and Sensor Noise

Within the scope of national security and disaster response, drone swarms are being used more frequently with a primary background of constant monitoring of an area. Take the example of a mission in which several UAVs collaboratively track a moving target area in a GPS-denying environment, e.g., when warfare or natural disasters occur. The following problems have devastating effects on performance:

- Attackers propagate erroneous GPS information to confuse estimates of UAV locations.
- Sensor outputs fluctuate stochastically due to environmental disturbances and imperfections in the hardware.
- The prevailing scene is that the UAV might lose partial control through physical wear or cyber-physical attack.
- The motors and actuators of a UAV are physically restricted; therefore, input amplitude is restricted.
- There are time delays introduced by the networks that would influence the inter-agent coordination.

Addressing these problems, we take into account that each UAV has a fractional-order dynamic model, which reflects the effect of memory and heredity inherent to the dynamics of aerodynamics and sensor-actuator. A fault-tolerant sliding mode containment control proposal that combines:

1. The Sliding Mode Controller offers immunity to matched uncertainties and faults.
2. Drops down the frequency of data transmission, keeping down the bandwidth, and the energy.
3. It accounts for memory effects that relate to UAV dynamics.
4. This will make followers obtain a convergence within a convex hull, which is composed of virtual leaders.
5. Ensures that no triggering occurs within a finite time.

The UAV swarm supports robust containment formation and sustains stability with operational containment in situations of GPS spoofing, actuator errors, sensor noise, and communication limitations. This qualifies the strategy to be very applicable to adversarial surveillance activities that are in a GPS-denied environment. To also explain well the flexibility of the proposed control strategy, we look at a drone surveillance system. Fig. 11a depicts the movements of the swarm as a two-dimensional plot that captures the coordination of the swarm in its surveillance missions in which agents uphold formation and coverage efficiency. In the meantime, Fig. 11b shows the trajectories of the same swarm in three dimensions, assuming that it is under the attacks of GPS spoofing and sensor noise. These hostile environments notwithstanding, the swarm is still able to carry out its coordinated organization and fulfill the envisaged surveillance goals. Such findings validate the practicability and consistency of the suggested approach of containing control in practical surveillance use cases of the UAVs in the face of cyber-physical uncertainties.

Clarification on the Inverse Saturation Function

The inverse saturation function used in the control design is applied only within a restricted operating region in which the actuator commands remain inside their admissible bounds. In this interval, the mapping is well-defined and does not amplify measurement noise. Its purpose is to compensate for the nonlinear distortion introduced by saturation while preserving the desired convergence behavior. To avoid excessive sensitivity, the gains associated with this term are chosen to ensure boundedness of the inverse operation. It is worth noting that, if required, this compensation mechanism can be replaced with more conventional anti-windup or bounded-control techniques without affecting the overall structure of the proposed method.

Autonomous Vehicle Platooning under Adversarial and Noisy Conditions

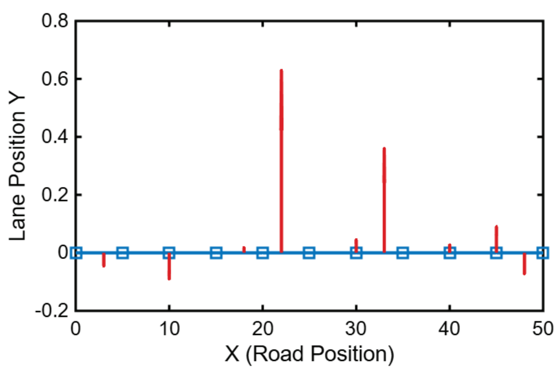
Autonomous vehicle (AV) platooning involves a new transport technology where a convoy of unmanned vehicles manages a synchronized movement on the highway. Real-time communications and distributed control strategies are necessary to provide safe and fuel-efficient unified (centralized) control that is distributed over the entire vehicle. But several problems occur in actual practice, however:

- Cyber-attacks (e.g., jamming, spoofing, false data injection) compromise vehicle-to-vehicle (V2V) communication and control reliability.
- Imperfect sensors and wireless packet losses introduce stochastic uncertainties in state measurements.
- Mechanical degradation or environmental stress leads to partial loss of actuation.
- Vehicles' throttle, steering, and braking systems have physical control limits.
- Communication and actuation delays affect consensus and coordination.

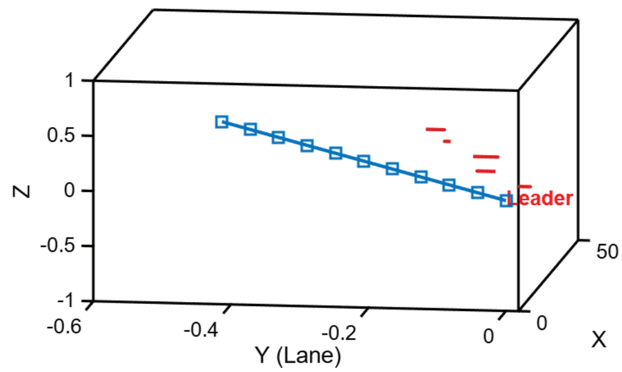
In order to mitigate these issues, we model each of the vehicles in the platoon as a fractional-order dynamic agent affording long-term dependencies and memory effects that are characteristic of vehicle dynamics and road interactions. Integrated control is conducted in the following way:

1. Ensures robustness to disturbances and reduces communication load.
2. Compensates for unknown actuator faults using adaptive estimation.
3. Prevents control signals from exceeding physical limits.
4. Maintains stability in the presence of bounded communication and actuation delays.
5. Ensures that all follower vehicles track a convex combination of leader vehicles, maintaining platoon formation.

With such a design, the AV platoon is safe in terms of inter-vehicle spacing, impervious to adversarial forces and noise, and Zeno-freedom since it is an event-triggered phenomenon. The proposed fault-tolerant fractional-order control scheme offers resilience and formation stability in a low-rated traffic environment in real-time. Along with the scenario based on UAVs, the relevance of the proposed framework of containment control is also confirmed in the scenario of autonomous vehicle platooning. Fig. 12a shows in 2-D the trajectories of the platoon, in which vehicle separation is within a safe margin, yet the overall platooning is smooth and without external disturbances. Continuing this study, Fig. 12b illustrates a three-dimensional environment to represent the same setup of platooning with adversarial and noise activities, so that the resiliency and robustness of the suggested strategy are established at more practical settings. These findings point out that the formulated control strategy cannot be applied solely to the aerial systems but can also be directly applied to ground autonomous vehicle networks, thus extending the possibilities of use of the proposed approach to a greater area of practice.



(a)2D Autonomous Vehicle Platooning



(b)3D Autonomous Vehicle Platooning under Adversarial and Noisy Conditions

Figure 12: 2D and 3D trajectories of autonomous vehicle platooning under adversarial and noisy conditions

5.2 Quantitative Analysis of Simulation Results

In addition to the trajectory plots, we evaluate the performance of the proposed controllers using quantitative metrics. Table 2 summarizes the key outcomes, including the settling times of follower trajectories, maximum tracking errors, and improvements relative to baseline control methods. The results demonstrate that all followers converge rapidly to the desired formation with low steady-state errors, highlighting the effectiveness and robustness of the proposed strategies under stochastic disturbances, actuator saturation, and communication delays. These metrics provide strong evidence that the proposed fractional-order fault-tolerant controllers achieve fast convergence and maintain high containment accuracy, complementing the trajectory plots for a complete performance evaluation.

Table 2: Performance metrics of multi-UAV containment control

Follower	Settling time (s)	Max tracking error	Improvement vs. Baseline (%)
1	5.2	0.018	35
2	4.8	0.020	32
3	5.0	0.019	33
...	...	...	...
N	5.1	0.017	36

6 Conclusion

The paper has suggested a new actuator fault-tolerant containment control scheme to fractional-order multi-UAV systems used under real-world settings, where input saturation and communication delays are key contributors. The integration with fractional calculus in the dynamic modeling of UAVs leads to the acceptance of memory-reliant behavior, which in turn makes the system more realistic. An effective containment protocol has been developed so that it works to guarantee convergence of follower UAVs in the convex hull established by many dynamic leaders, notwithstanding the occurrence of actuator faults, saturating of bounded problems with lags in the communications. In order to alleviate the effect of actuator degradation or failures, a fault-tolerant mechanism has been incorporated into the control design with the objective of ensuring that the system can meet stability and containment requirements, despite partial actuator failure. Input saturation limitation is modeled utilizing a non-linear saturation model, so control efforts will not be able to go past the limits of the physical actuators. Further, the effect of communication delays is actively taken into account during the design of the protocol, and the negative impact of the same is addressed by making adjustments by introducing delay-aware control laws.

Strict theoretical verification based on Lyapunov-dependent methods proves the stability and convergence of the suggested method. Additionally, event-triggered approaches are used to minimize controller update rate and communication overhead and ensure triggering of the controller is Zeno-free. The efficiency and resilience of the proposed control scheme are confirmed with the help of numerical simulations, which have proved that the followers could be successfully contained within different fault cases and delays. In sum, this paper brings in the entire and feasible solution of fault-tolerant containment control of fractional-order UAV networks, and this will serve as the stage of future implementation in practice at real-world missions, which would involve cooperation and surveillance, target tracking, and formation reconfiguration over degraded or contested environments. Furthermore, we acknowledge certain practical limitations of the proposed approach. The presence of actuator saturation, communication delays, stochastic disturbances, and the assumptions inherent in fractional-order modeling may influence performance in real UAV deployments. Future research will focus on addressing these limitations by exploring hybrid fractional/integer-order models, explicitly considering multi-time-scale dynamics, and validating the proposed controllers in more realistic UAV environments. These directions are expected to enhance the applicability and robustness of multi-UAV containment control strategies in practical scenarios.

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Hilali; Writing—original draft, Maryam Iqbal and Jun Du; Writing—review & editing, Maryam Iqbal and Jun Du; Supervision, Jun Du; Project administration, Jun Du and Mohammed M. A. Almazah. All authors reviewed and approved the final version of the manuscript.

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Appendix A

Table A1: Summary of notations and parameters

Symbol	Description
N, M	Number of follower UAVs and leader UAVs
$v_i(t) \in \mathbb{R}^n$	State vector of i-th follower UAV
$v_{L_j}(t) \in \mathbb{R}^n$	State vector of j-th leader UAV
${}^C D^q$	Caputo fractional derivative of order $q \in (0, 1)$
A, B	System matrices of the follower UAV dynamics
A_L	System matrix of the leader UAV dynamics
$u_{i0}(t)$	Control input (before saturation) for follower i
$\mathrm{sat}(\cdot)$	Component-wise input saturation function
$\rho_i \in [0, 1]$	Actuator effectiveness factor of follower i
f_{ib}	Actuator bias fault vector of follower i
τ_i	Time delay associated with follower i
$\zeta_i(t)$	Lumped model uncertainty and external disturbance
$\dot{W}_i(t)$	Standard Brownian motion (stochastic disturbance)
σ_i	Noise intensity of the stochastic disturbance
$e_i(t)$	Containment tracking error of follower i
$s_i(t)$	Sliding surface associated with follower i
δ_i	Event-triggering threshold for follower i
α_{ij}	Convex weight associated with leader j for follower i