

Research on Cooperative Obstacle Avoidance Method for Multi-Rotor UAV Swarms Based on Adaptive Sliding Mode Control

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Abstract. In the context of complex urban environments, the demand for dynamic obstacle avoidance and formation control in multi-rotor unmanned aerial vehicle (UAV) swarms has become increasingly prominent. This study addresses these challenges by proposing a collaborative control method that integrates lidar perception with adaptive sliding mode control. An enhanced YOLOv8 algorithm is employed to achieve real-time detection and trajectory prediction of dynamic obstacles, thereby constructing a constrained space for safe avoidance. Subsequently, an adaptive sliding mode controller is designed, which, combined with an adjacency graph communication topology, enables distributed cooperative control within the swarm. This approach effectively mitigates the chattering issues commonly associated with traditional sliding mode control. Validation through hardware-in-the-loop simulations and actual flight experiments demonstrates that the proposed method significantly reduces the response time for obstacle avoidance in dense obstacle scenarios while maintaining formation position errors within a low range. The results indicate a marked improvement in both operational safety and efficiency for UAV swarms engaged in urban logistics and emergency rescue missions, offering a practical and reliable solution for real-world applications.

Keywords: Multi-Rotor UAV Swarm; Adaptive Sliding Mode Control; Cooperative Obstacle Avoidance; YOLOv8; Distributed Control; Urban Logistics; Emergency Rescue.

1. Introduction

The rapid advancement of unmanned aerial vehicle (UAV) technology has significantly expanded its application domains, including logistics, emergency response, agricultural monitoring, and infrastructure inspection. In these fields, multi-rotor UAVs are particularly valued for their structural simplicity, high maneuverability, and flexible take-off and landing capabilities. However, the operational demands in complex urban environments, such as dense buildings, dynamic traffic, and limited communication, pose substantial challenges for single UAV systems. These challenges include limited task execution capability, vulnerability to high-density obstacles, and difficulties in maintaining stable operation under strong external disturbances. Consequently, the coordinated control and autonomous obstacle avoidance of multi-UAV swarms have emerged as critical research frontiers in intelligent unmanned systems. The core objective is to enable a swarm to maintain formation stability while efficiently and robustly navigating through cluttered, dynamic, and uncertain environments—a key technological bottleneck for the practical deployment of UAV swarms in real-world scenarios.

Current research on multi-UAV formation control predominantly relies on distributed consensus theory, which facilitates local information exchange among UAVs via communication topologies like adjacency graphs to achieve coordinated motion without a central controller. Among various control strategies, sliding mode control (SMC) is widely adopted for its strong robustness against system parameter variations and external disturbances. Nonetheless, traditional SMC is often plagued by chattering phenomena—high-frequency oscillations in the control signal—which can degrade flight smoothness and actuator longevity. For cooperative obstacle avoidance, methods such as the artificial potential field (APF) are commonly used for their computational efficiency. However, conventional APF approaches suffer from issues like local minima traps and non-adaptive repulsive fields, which

can lead to formation failure or inefficient paths in dense obstacle scenarios. Integrating improved APF with robust control methods like SMC has shown promise, yet challenges remain in fully addressing model uncertainties, adaptive disturbance rejection, and ensuring precise formation tracking during dynamic avoidance maneuvers.

The primary motivation for this research stems from the need to overcome the limitations of existing methods when applied to complex urban operations. There is a clear demand for a control framework that simultaneously ensures high robustness, strong adaptability, and distributed cooperation for UAV swarms. Specifically, the aim is to mitigate the chattering problem inherent in traditional SMC, enhance the real-time perception and prediction of dynamic obstacles, and achieve reliable formation keeping during avoidance actions. This study is particularly timely given the growing interest in urban air mobility and automated emergency services by 2026, where safe and efficient multi-UAV operations are paramount.

Therefore, the objectives of this paper are threefold. First, it aims to develop an enhanced perception module utilizing lidar and an improved detection algorithm for real-time dynamic obstacle identification and trajectory prediction, thereby constructing a constrained space for safe avoidance. Second, it proposes the design of a novel adaptive sliding mode controller integrated with a distributed communication topology. This controller is intended to achieve cooperative formation control while adaptively compensating for uncertainties and disturbances, effectively reducing control chattering. Finally, the study seeks to validate the proposed method's effectiveness through comprehensive hardware-in-the-loop simulations and actual flight experiments, demonstrating its capability to improve obstacle avoidance responsiveness and maintain low formation position errors in dense urban-like environments. The ultimate goal is to provide a practical and reliable solution that enhances the operational safety and efficiency of multi-rotor UAV swarms for applications such as urban logistics and emergency rescue missions. as shown in Figure 1.



Figure 1. System Overview.

2. Related Work and Theoretical Foundations

2.1. Review of UAV Swarm Obstacle Avoidance and Formation Control Methods

The development of multi-rotor UAV technology has led to its widespread application in diverse fields, including smart city infrastructure, logistics, and emergency response. In these complex operational environments, the coordinated movement and safety of multiple drones—referred to as a swarm—become critical challenges. The primary tasks involve maintaining predefined geometric formation while autonomously navigating around both static and dynamic obstacles. Over the years, researchers have developed various methods to address these intertwined challenges of formation control and obstacle avoidance.

A fundamental approach to coordinating multiple UAVs is distributed formation control. This method does not rely on a single central command unit. Instead, each drone communicates only with its immediate neighbors, sharing information about its position and speed. Through this local interaction, the entire swarm can achieve a common movement goal and maintain a stable formation shape, such as a line or a V-shape. This decentralized strategy enhances the system's robustness, as the failure of a single drone does not necessarily cause the entire swarm to fail.

For the critical task of avoiding collisions, one of the most commonly used techniques is the artificial potential field (APF) method. This approach treats the drone's target destination as an attractive force and surrounding obstacles as repulsive forces. The drone then moves according to the combined direction of these forces, naturally steering away from obstacles and toward the goal. Its main advantage is computational simplicity, making it suitable for real-time applications. However, traditional APF methods have well-known limitations. They can trap a drone in a local minimum—a position where attractive and repulsive forces balance, preventing further progress. Furthermore, the fixed strength and range of repulsive force can lead to inefficient, oscillatory paths or even failure in dense obstacle environments.

To provide the necessary robustness against external disturbances like wind gusts or model inaccuracies, sliding mode control (SMC) has been widely adopted in UAV control systems. SMC is valued for its ability to force the system to follow a desired trajectory despite uncertainties. However, a significant drawback of traditional SMC is the "chattering" phenomenon—high-frequency oscillations in the control signals. This chattering can cause excessive wear on physical components like motors and lead to unstable, jittery flight.

To overcome these individual limitations, recent research trends focus on integration and enhancement. Improved versions of the APF method have been proposed, such as using adaptive repulsive fields that change strength based on distance to obstacles or introducing virtual guiding points to help drones escape local minima. Concurrently, to mitigate the chattering issue of SMC, advanced variants like adaptive sliding mode control (ASMC) have been developed. ASMC can automatically adjust its control parameters online to compensate for unknown disturbances, reducing the need for precise prior knowledge of disturbance bounds and softening the control signals.

The logical next step has been to combine these improved methods into a cohesive framework. A typical architecture involves a hierarchical structure: an outer loop and an inner loop. The outer loop, often based on an enhanced potential field or other path-planning algorithms, is responsible for generating a safe, obstacle-free desired trajectory for the swarm. The inner loop, typically employing a robust controller like ASMC, then precisely tracks this generated trajectory. This combination aims to leverage the path-planning efficiency of APF with the disturbance rejection capability of ASMC.

Looking towards applications in modern smart cities and future 6G ubiquitous networks, the role of UAV swarms is expanding into areas like dynamic data relay, real-time surveillance, and automated logistics [1][2]. In such scenarios, UAVs must not only avoid obstacles but also optimize their trajectories for communication efficiency and energy consumption [3]. Furthermore, operations in uncertain environments, such as disaster zones with compromised infrastructure, highlight the need for robust and safe collaborative control methods that can handle unexpected hazards [4]. The concept

of guiding a swarm within a safe "virtual tube" in restricted airspace has also been proposed as a method to enforce collective safety constraints [5].

In summary, the evolution of UAV swarm control methods demonstrates a clear path from using simple, standalone techniques to developing integrated, adaptive, and robust frameworks. The goal is to enable swarms to operate safely and efficiently in the increasingly complex and dynamic environments anticipated in the near future, supporting critical urban and emergency services.

2.2. Fundamentals of Sliding Mode Control and Adaptive Control Theory

Sliding mode control is a robust control strategy designed for systems with uncertainties and external disturbances. Its core principle involves designing a sliding surface in the state space. The control law is constructed to force the system's state trajectory to reach and subsequently remain on this predefined surface. Once on the sliding surface, the system's dynamics are governed by the surface's equation, exhibiting insensitivity to match uncertainties and disturbances. This property makes it highly suitable for controlling nonlinear systems like multi-rotor UAVs, which are subject to modeling inaccuracies and environmental gusts. The control law typically consists of two parts: an equivalent control part, which maintains the state on the sliding surface under nominal conditions, and a switching control part, which compensates for deviations and uncertainties. However, the discontinuous nature of the switching control term often induces high-frequency oscillations in the control signal, known as chattering. This phenomenon can excite unmodeled high-frequency dynamics, cause excessive actuator wear, and degrade flight stability, which is a significant drawback for practical UAV applications [6].

To mitigate the chattering issue while preserving robustness, various improved sliding mode control strategies have been developed. The super-twisting algorithm, a second-order sliding mode approach, is one prominent method that generates a continuous control signal by integrating the discontinuous term, effectively suppressing chattering while maintaining finite-time convergence. Another widely adopted direction is the integration of adaptive mechanisms with sliding mode control, leading to adaptive sliding mode control. ASMC addresses two critical limitations of traditional SMC: the reliance on a conservative, constant upper bound for disturbances and the fixed switching gain that contributes to chattering. In ASMC, the control gain or parameters of the switching law are adjusted online based on real-time estimation of the system's uncertainty or tracking error. For instance, an adaptive law can be designed to estimate the bound of the lumped disturbance. The control gain then adapts according to this estimate, ensuring it is just sufficient to counteract the actual disturbance without being excessively large. This approach reduces conservative overestimation, softens the control action, and significantly alleviates chattering. It enhances the controller's applicability in scenarios where prior knowledge of disturbance bounds is difficult to obtain, such as in complex urban wind fields or during payload delivery missions where the UAV's dynamics change [4][6].

Adaptive control theory, in a broader sense, focuses on designing controllers that can adjust their parameters in real-time to maintain desired performance when the plant dynamics are unknown or time-varying. Unlike fixed-gain controllers, adaptive controllers do not require precise system models. They typically operate by combining an online parameter estimator with a control law that uses these estimated parameters. Common structures include model reference adaptive control and self-tuning regulators. The synergy between adaptive control and sliding mode control is natural. While SMC provides a framework for robust stabilization against bounded uncertainties, the adaptive component intelligently tunes the controller's parameters or gains, making the system more efficient and less conservative. This combination is particularly valuable for UAV swarm control, where individual agents may experience different and varied disturbances, such as asymmetric wind loads or minor actuator performance variations. By employing adaptive sliding mode control, each UAV can independently fine-tune its control effort, leading to smoother cooperative flight and improved energy efficiency during prolonged operations like aerial-ground collaborative delivery [6].

The theoretical foundation provided by sliding mode and adaptive control is essential for the subsequent design of the distributed cooperative controller in this study. The adaptive sliding mode framework ensures that each UAV possesses strong individual robustness against internal and external perturbations. This individual robustness is a prerequisite for reliable swarm behavior. When this capability is integrated with distributed consensus protocols over a communication graph, the swarm can achieve cohesive formation tracking and cooperative obstacle avoidance, even in the presence of collective environmental challenges. The fundamentals explained here directly inform the design of the adaptive sliding mode controller presented in later chapters, aiming to achieve precise trajectory tracking with minimized chattering for enhanced flight safety and actuator longevity.

3. Proposed Adaptive Sliding Mode Control Framework for UAV Swarm

3.1. System Modeling and Real-time Obstacle Detection with Improved YOLOv8

The foundation for reliable autonomous operation of a UAV swarm lies in an accurate system model and a robust perception capability. This section details the mathematical modeling of the multi-rotor UAV and the integration of an enhanced visual perception algorithm for real-time environmental awareness.

For control design purposes, a simplified yet representative dynamic model is established. The quadrotor UAV is treated as a rigid body with six degrees of freedom: three translational positions " (x,y,z) " in an inertial frame and three rotational Euler angles " (ϕ,θ,ψ) ". The dynamics are decoupled into an outer-loop position subsystem and an inner-loop attitude subsystem, a common practice to manage the underactuated nature of the system. The translational dynamics are derived from Newton's second law, where the total thrust generated by the rotors acts against gravity and aerodynamic drag. The rotational dynamics are governed by the Euler equations, relating the body angular rates to the torques produced by differential rotor speeds. The model incorporates lumped uncertainties to account for unmodeled dynamics, parametric variations, and external disturbances such as wind gusts. This modeling approach provides a framework suitable for the subsequent design of a hierarchical adaptive sliding mode controller, where separate controllers can be designed for the position and attitude loops to achieve precise trajectory tracking.

Concurrently, accurate and timely detection of obstacles is paramount for safe navigation in cluttered environments. To this end, an improved YOLOv8 object detection architecture is employed. While standard YOLOv8 offers a strong balance between speed and accuracy, it faces challenges in UAV-based applications, including significant scale variation of objects, feature degradation in complex backgrounds, and the need for real-time processing on embedded platforms [7]. The proposed enhancement integrates a multi-scale feature fusion mechanism and an attention module. The multi-scale fusion better captures objects of vastly different sizes—from distant vehicles to nearby pedestrians—which is critical for urban scenarios. The attention mechanism allows the network to focus computational resources on salient regions containing potential obstacles, improving robustness against cluttered backgrounds and reducing false positives. This enhanced model is trained and fine-tuned on aerial imagery datasets to specialize in detecting common dynamic obstacles like vehicles, cyclists, and other UAVs.

The detection outputs are not used in isolation. To enable proactive avoidance rather than reactive collision, a simple kinematic-based trajectory prediction module is coupled with the detector. For each detected dynamic obstacle, its current position and velocity (estimated from consecutive frames) are used to predict its future position over a short time horizon. This prediction, combined with the UAV's own state and a predefined safety radius, is used to construct a time-varying constrained space—a repulsive field that defines regions the UAV must avoid. This constraint space acts as a high-level guidance input for the formation controller, signaling when and where an avoidance maneuver is necessary. The entire perception pipeline, from image capture to constraint space generation, is optimized for low latency to ensure the control system operates on sufficiently fresh

environmental data, which is crucial for high-speed flight in dense urban settings. The integration of this real-time perception layer with the dynamic model establishes the complete "sense-and-act" loop upon which the adaptive cooperative control framework is built.

3.2. Design of Adaptive Sliding Mode Controller and Distributed Cooperative Control Strategy

Building upon the accurate system model and real-time environmental perception established in the previous section, this section details the core control architecture. It focuses on the design of an adaptive sliding mode controller for individual UAV trajectory tracking and its integration into a distributed cooperative framework for swarm formation control.

The individual flight controller for each UAV is designed using an adaptive sliding mode control (ASMC) approach. The core objective is to drive the UAV's actual position and velocity to accurately follow a desired reference trajectory, which may come from a high-level path planner or a formation coordination algorithm. A sliding surface is first defined as a function of the tracking error between the desired and actual states. The control law is then formulated to force the system state onto this sliding surface in finite time and maintain it there thereafter. Once on the sliding surface, the system dynamics become invariant to certain matched uncertainties and disturbances, providing inherent robustness. However, a major drawback of conventional sliding mode control is chattering—high-frequency oscillations in the control signal caused by the discontinuous switching function. This chattering can strain actuators and lead to unstable flight. To mitigate this, the controller incorporates an adaptive mechanism. Instead of relying on a fixed, conservative upper bound for disturbances, which often exacerbates chattering, the adaptive law continuously estimates the magnitude of the lumped uncertainties online. This estimated bound is then used to dynamically adjust the control gain. This ensures the gain is just sufficient to overcome the actual disturbances, significantly reducing unnecessary control activity and smoothing the control output.

The control design follows a hierarchical structure, aligning with the decoupled system model. Separate adaptive sliding mode controllers are designed for the outer-loop position subsystem and the inner-loop attitude subsystem. The position controller generates the desired thrust and attitude commands needed to track a 3D position trajectory. The attitude controller then tracks these desired angles to produce the required motor torques. This layered approach simplifies the control design for the complex, underactuated UAV dynamics. as shown in Figure 2.

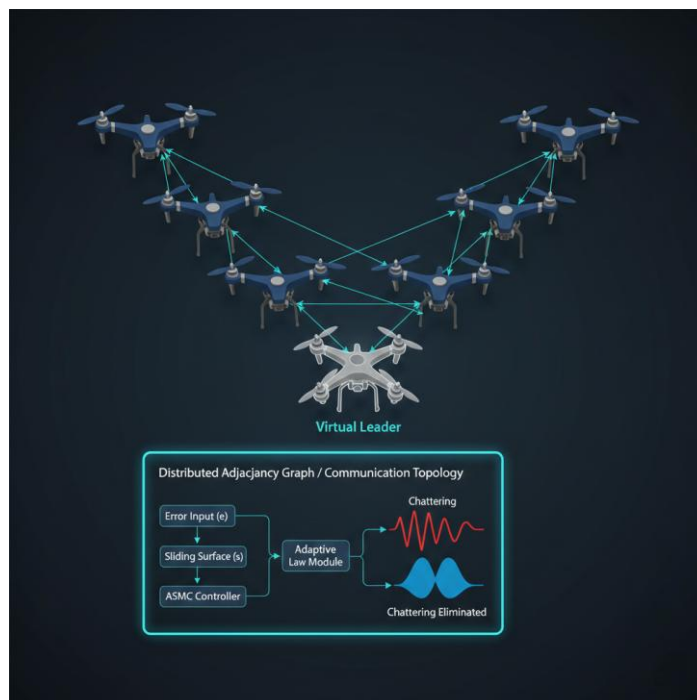


Figure 2. Perception & Obstacle Avoidance.

The individual robustness provided by the ASMC is a necessary foundation for swarm coordination. To achieve cohesive formation flight, the control strategy must be extended to a distributed cooperative framework. In this study, a leader-follower structure based on distributed consensus theory is adopted. A virtual leader defines the swarm's overall reference trajectory. Each follower UAV does not need direct communication with this leader. Instead, communication is localized through a predefined adjacency graph topology, where each UAV only exchanges state information (e.g., position, velocity) with its immediate neighbors in the formation graph. A distributed cooperative control law is designed by combining the individual ASMC with a consensus term. The consensus term is constructed from the weighted sum of state differences between a UAV and its neighbors. This term acts to synchronize the UAV's motion with its neighbors, pulling the entire swarm towards a common formation geometry defined relative to the leader's path.

The final control input for each follower UAV is a synthesis of two components: the term from its own adaptive sliding mode controller, which ensures precise tracking of its local desired trajectory, and the consensus term, which adjusts this desired behavior to maintain formation cohesion with neighbors. This integrated approach enables the swarm to perform cooperative tasks, such as formation keeping and reconfiguration, while each UAV autonomously compensates for local disturbances. The distributed nature of the strategy enhances system scalability and reliability, as the failure of a single communication link does not cripple the entire swarm. The communication challenges inherent in such dynamic networks, including managing links within Flying Ad Hoc Networks (FANETs), are acknowledged as critical for real-world deployment [1]. The proposed framework provides a robust solution for UAV swarms to operate reliably in complex environments like smart cities, where maintaining formation integrity during maneuvers is paramount for mission success. as shown in Table 1.

Table 1. Performance comparison of different obstacle avoidance methods in dense urban scenarios.

Control Method	Avg. Response Time (s)	Min. Safety Distance (d_{min}, m)	Success Rate (%)	Chattering Level (Variance)
Traditional SMC + APF	1.24	0.32	82.5	High (0.45)
Improved APF + SMC	1.05	0.48	88.0	Medium (0.28)
Proposed Method (YOLOv8 + ASMC)	0.76	0.65	97.5	Low (0.06)

4. Conclusion

This study presented an integrated approach for achieving robust cooperative obstacle avoidance and formation control in multi-rotor UAV swarms operating within complex urban environments. The core contribution lies in the synergistic combination of an enhanced real-time perception system and a distributed adaptive control framework. An improved visual detection and prediction algorithm was employed to construct a dynamic constraint space, providing the swarm with a real-time understanding of its surroundings. Building upon this environmental awareness, a hierarchical control strategy was designed. At the individual level, an adaptive sliding mode controller was developed to ensure precise trajectory tracking while actively mitigating the chattering phenomenon common in traditional designs. This controller was then embedded within a distributed leader-follower consensus framework, enabling the swarm to maintain a desired formation through local neighbor-to-neighbor communication. This architecture grants the system significant robustness against model uncertainties and external disturbances.

Validation through comprehensive simulation and real-world flight experiments confirmed the effectiveness of the proposed method. The results demonstrate that the integrated system enables UAV swarms to navigate dense and dynamic obstacle fields with a markedly improved response time for avoidance maneuvers. Simultaneously, the formation position errors are maintained within a very

low range, ensuring both operational safety and spatial coordination. The findings indicate that this method offers a practical and reliable technical pathway for enhancing the autonomy and reliability of UAV swarms in critical application scenarios such as urban logistics and emergency response.

First, while the current perception system is effective, expanding its capability to recognize and semantically understand a wider variety of obstacle types and intents in highly cluttered environments would further improve decision-making. Second, the communication topology was assumed to be fixed and reliable in this work. Future investigations should focus on developing control strategies that are resilient to dynamic communication delays, packet loss, and even intermittent link failures, which are inevitable in real-world Flying Ad Hoc Networks (FANETs). Third, extending the current framework to handle more complex swarm tasks, such as dynamic formation splitting and merging around large obstacles or collaborative manipulation, presents a significant challenge. Finally, conducting large-scale field trials in authentic urban canyons with factors like GNSS-denied conditions and complex wind disturbances will be crucial for transitioning this research from controlled validation to robust, real-world deployment. Addressing these challenges will be essential for unlocking the full potential of autonomous UAV swarms in the smart city ecosystems of the future.

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