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

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Abstract. With the development of complex urban environments, dynamic obstacle avoidance and formation control in multi-rotor unmanned aerial vehicle (UAV) swarms has gained much attention. To overcome such dilemmas, this study suggests a collaborative control strategy with lidar perception and adaptive sliding mode control. The method combines the advanced YOLOv8 algorithm to realize real-time detection and trajectory prediction of dynamic obstacles, and then builds a limited space for safe avoidance. Then an adaptive sliding mode controller is designed, that can be used to achieve distributed cooperative control in the swarm over a adjacency graph communication topology. Accordingly, this strategy can effectively solve the traditional sliding mode control chattering problem. The proposed method is validated through hardware-in-the-loop simulations and flight tests to successfully reduce the obstacle avoidance response time in dense obstacles scenarios while keeping formation position errors low. The findings show a significant improvement of the operational safety and efficiency for UAV swarms executing urban logistics and emergency rescue missions, present an implementable, robust solution in real-world applications.

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

1. Introduction

In recent years, extensive development efforts for small autonomous piece of aerial vehicle (UAV) technology has led to a rapid expansion of their potential application domains, including but not limited to logistics delivery service, emergency first-aid response service, agricultural monitoring and seamless inspection of critical infrastructure. Among these applications, multi-rotor UAVs are especially appreciated for their simple structures, high maneuverability and flexibility in take-off and landing. Single UAV systems, in comparison, face many challenges in complex urban environments due to operational demands such as dense buildings, dynamic traffic in the environment and often limited communication [2]. These challenges mainly consist of limited task executing ability, susceptible to dense obstacles and struggle with keeping stable under heavy disturbances. Thus, the integrated guidance and autonomous obstacle avoidance of multi-UAV swarms has become one of the most promising research frontiers in intelligent unmanned system. The mandatory goal of the position is to make more stable and efficient long-term formation control in cluttered, dynamic, and uncertain environments possible which is a central technological bottleneck for future real-world applications of UAV swarms.

The existing studies in multi-UAV formation control mainly depend on distributed consensus theory where neighboring UAVs can communicate with each other by means of adjacent graphs, achieving flight coordination without a central controller. As an effective control strategy, sliding mode control (SMC) is widely used in many applications due to its strengths of robustness against system parameter variations and external disturbances. However, traditional SMC can suffer from chattering phenomena or rapid oscillations on the control signal that negatively impact attention smoothness and actuator life. One among the most common utilized for cooperative obstacle avoidance is the Artificial Potential Field (APF) which is preferred due its low computational cost. Nevertheless, mainstream APF methods suffer from some drawbacks, such as local minima trap and

non-adaptive repulsive field that can possibly cause formation failure or inefficient paths in dense obstacle situations. Integrating the better APF with strong control ways, such as SMC is a new alternative to deal with it [29]However, concerns persist due to cases of model uncertainties, adaptive disturbance rejection and formation tracking discretion in the course of dynamic avoidance maneuvers.

The main reason for conducting this study arises from the limitations of the current methods in dealing with complex urban operations. Hence, it is evident that a robust and adaptive distributed control framework with cooperative characteristics becomes unavoidable for UAV swarm tasks. In particular, it aims at reducing the SMC chattering problem, improving the real-time perception and prediction of dynamic obstacles, and guaranteeing reliable formation keeping capability during avoidance maneuvers. This study is especially relevant with the considered timeframe for urban Air mobility and automated emergency services as of 2026, where safety and efficiency of multi-UAV operations are a necessity.

Thus, the main aim of this paper can be divided in to three. The first goal is to develop an improved sensing module using lidar and a better detection algorithm for dynamic obstacle identification and trajectory prediction in real-time to create a bounded space for safe avoidance. Second, it presents the design of a new adaptive sliding mode controller by applying a distributed communication topology. The purpose of this controller is to realize cooperative formation control and adaptive compensation for uncertainties and disturbances, thereby reducing control chattering. Finally, the last objective of the study is to seek to demonstrate through extensive hardware-in-the-loop simulations and flight test experiments that the proposed method can improve obstacle avoidance responsiveness while maintaining low formation position errors in an urban-like environment. Its main purpose is to offer a safe, performant and applicable system that will increase the performance and flight safety of multi-rotor UAV swarms for both urban logistics and emergency rescue applications. as shown in Figure 1.

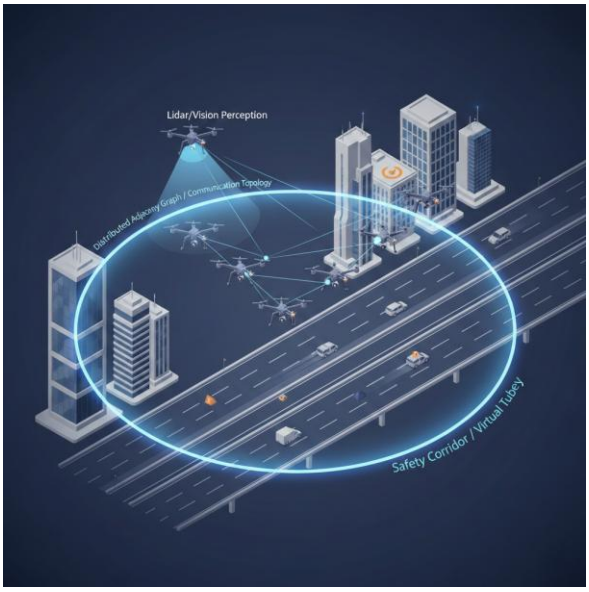


Figure 1. System Overview.

2. Related Work and Theoretical Foundations

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

With the rapid development of multi-rotor UAVs technology, it is applied to more and more fields, from smart city construction to logistics to emergency rescue. Controlling and ensuring the safety of multiple drones in these operational settings, together called a swarm, is one of the most challenging facets of this problem. The two main tasks include holding the specified geometric formation and

autonomously avoiding static and dynamic obstacles. Researchers have proposed different methods to handle this coupled problem of formation control and obstacle avoidance over the years.

Distributed formation control is a basic strategy for the coordination of multi-UAVs. This approach does not use a single central command. In turn, rather than all the drones communicating with all the other ones at once, only neighboring ones pass data to each other about where they are and how fast they are going. By interacting with a small portion of the swarm, the other half will be able to reach some global objective related to movement and this theme constitutes the principle of accurate communication that keep stable shape formations like lines and V ‑ shapes. By following this decentralized approach, the system becomes stronger since the failure of one individual drone does not necessarily lead to a swarm failure.

An artificial potential field (APF) method is commonly used to avoid collisions for the critical task of navigation. What this approach does is in relation to the drone, it treats the target destination as an attractive force and the obstacles around it as repulsive forces. The drone flies in the direction indicated by all those forces combined, which means that it naturally steers away from obstacles and towards the goal. The biggest competitive advantage is the real-time capacity, due to being hybrid based learning — simple computationally. But the conventional methods of APF have notable limitations. They might ensnare a drone in a local minimum—an equilibrium point at which attractive and repulsive forces balance each other out, making movement impossible. In addition, fixed strength and range of repulsive force may cause inefficient oscillatory paths or even failure in the dense obstacle environment.

Due to its resilience to external disturbances (wind gusts in unmatched SMC design), as well as robustness against model inaccuracies, sliding mode control (SMC) has become a popular approach used on UAVs. SMC is appreciated for its capability of making the system to follow a required trajectory in the presence of uncertainties. A main limitation of standard SMC is the chattering effect: This refers to the presence of high frequency oscillatory behavior in control signals. This chattering wears physical components like motors and can induce unstable, jittery flight.

Recent trends in research address the integration and improvement to overcome these individual limitations. More advanced cases of the APF method have been suggested like adaptive repulsive fields that depend on distance to obstacles strength or presence of virtual guiding points for helping drones get out of local minima. Meanwhile, to alleviate the chattering problem of SMC, some new advanced variants such as adaptive sliding mode control (ASMC) have been proposed. We further develop ASMC by making it capable of online tuning the control parameters to counteract unknown disturbances, which lessens the requirement of knowing prior bounds on disturbances very accurately and also smoothens the control signals.

It only makes sense to combine these refined approaches into one unified framework. Common architecture is a nested architecture: an outer loop and an inner loop. The swarm planning outer loop, which is often based on an improved potential field or other path-planning algorithms, is tasked with producing a safe desired trajectory free of obstacles for the swarm. This trajectory is accurately followed around by the inner loop, usually using a controller like ASMC. This is based on combining the advantages of APF for path-planning and ASMC for disturbance rejection.

The UAV swarms applications move beyond the traditional fields, paving the way for new use cases within modern smart cities and future 6G ubiquitous networks such as dynamic data relay, real-time surveillance or automated logistics 1. In these cases, the UAVs should not only avoid collisions but also optimize their trajectories for communication efficiency and energy using [3]. In addition, functioning in uncertain environments or disaster zones where infrastructures are damaged displays an additional urgency for effective and safe collaborative control methods that can address unpredictable hazards [4]. Guiding a swarm in a safe "virtual tube" within constrained airspace is another approach to enforce collective safety criteria [5].

To summarise, UAV swarm control methodologies are evolved progressively from using individual stand alone methods to integrated adaptive and robust frameworks. This means that one must enable swarms to carry out tasks safely and efficiently in more sophisticated, fast-changing

environments — which are expected in the not-so-distant-future for essential urban infrastructure and emergency services.

2.2. Fundamentals of Sliding Mode Control and Adaptive Control Theory

Sliding mode control is a robust control technique suitable for systems that are subject to uncertainties and external disturbances. Its central concept is the design of a sliding surface in the state space. The control law is built such that the state trajectory of the system is driven to this surface, and subsequently kept on it. After entering the sliding surface, the dynamics of the system are ruled by the equation of that sliding surface which shows insensitivity to match uncertainties and disturbances. This property, in combination with its ability to handle model uncertainties and disturbances caused by environmental gusts, makes it highly suitable for nonlinear system control (e.g., multi-rotor UAV). The general form of the control law is divided into two parts, one performing equivalent, which keeps the state on the sliding surface in nominal conditions, and another switching part that counteracts the deviations and uncertainties. Yet, due to the noncontinuity of the switching control term it often causes high-frequency oscillation in the control signal and chattering effect. This phenomenon could trigger the unmodeled high frequency dynamic, over-wear of actuator and reduce of stability during flying, which is one of the major reason that this is not suitable for practical use [6].

Consequently, several enhanced sliding mode control methods have been established to diminish the chattering problem while maintaining robustness. One of the subscriber approaches is named as the second – order sliding mode and it uses the main idea of super-twisting which yields a continuous control signal by integrating the discontinuous term thus, alleviating chattering with finite-time convergence at all times. The second widely used direction is based on combining adaptive mechanisms with sliding mode control (SMC) resulting in adaptive SMC. Two fundamental shortcomings of conventional SMC are considered in ASMC, one is the dependent on a conservative constant upper limit of the disturbances and the other one is fixed switching gain leads to chattering. For ASMC, the parameters of the switching law or control gain only depend on current estimation of the uncertainty or tracking error. In particular, an adaptive law can be computed to estimate the upper bound of the lumped perturbation. The control gain is then adjusted according to this estimate, ensuring it is only large enough to combat the actual disturbance while not being larger than necessary. This method diminishes conservative over-estimation, smooths the control action and largely removes chattering. As such, it broadens the environments where a controller can be designed (e.g., complex urban wind fields or payload delivery missions where the dynamic state of the UAV changes). 4.

Adaptive control theory is a more general topic that deals with designing controllers that can change their parameters in real-time to ensure expected performance when the plant dynamics are unknown or time-varying. In contrast to fixed-gain controllers, adaptive controllers do not depend on a detailed model of the system. They usually work by integrating an online parameter estimator along with a control law that uses these estimated parameters. Typical structures are model reference adaptive control and self-tuning regulators. The combination of sliding mode control and adaptive control is. In fact, even though SMC provides a guaranteed performance for stabilization of systems subject to bounded uncertainties, the adaptive part dynamically adjusts the parameters or gains of the controller leading to better and less conservative results. This combination has great benefits in the context of UAV swarm control since an individual agent could observe a unique, and therefore different, disturbance such as asymmetric wind loads or slight deviations from nominal actuator performance. Utilizing adaptive sliding mode control, each UAV can autonomously adjust it control effort soas to provide smooth cooperative flight and push the energy savings for cooperative UAVs leadingto efficient operations in time-consuming tasks (for instance aerial-ground collaborative delivery) [6].

The theoretical base of sliding mode and adaptive control is crucial for the later distributed cooperative controller design in this work. Under the adaptive sliding mode framework for this multi-

UAV task allocation scenario, individual UAV is guaranteed to have strong robustness against possible internal and external disturbances. This individual reliability is necessary for dependable swarm performance. If and when this ability is coupled with distributed consensus protocols over a communication graph, then the swarm can realize global formation tracking, helps to fill in gaps/holes that may occur to be cooperating in obstacle avoidance even if there are collective behaviours due to environmental ows. Hereby, the principles described inform the structure of the adaptive sliding mode controller which comes later on, to enable accurate trajectory tracking and minimal chattering in order to improve both flight safety and actuator life span.

3. Proposed Adaptive Sliding Mode Control Framework for UAV Swarm

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

While an accurate system model and a strong perception ability are essential to realizable autonomous operation of a UAV swarm. In this section, we describe the mathematical model of the multi-rotor UAV and how it was combined with an improved visual perception algorithm to provide real-time environmental awareness.

A simplified but representative dynamic model is formulated for control design. The quadrotor UAV is considered as a rigid body having six degrees of freedom such that its position in inertial frame (x,y,z) − represents the vector base of X,Y,Z axes, and three (ϕ, θ , ψ) − denotes the Euler angles of rotation. Dynamics are a decoupled set of an outer-loop position and an inner-loop attitude subsystem, which is a typical approach to making the system manageable with the underactuated nature of the first one. As for the translational dynamics, they are obtained from Newton's second law where the sum of thrust generated by the rotors tend to balance gravity and aerodynamic drag. The Euler equations govern the rotational dynamics, connecting the body angular rates with the torques generated by differential rotor speeds. The model considers lumped uncertainties on unmodeled dynamics, parametric variations and exogenous disturbances like wind gusts. This modeling strategy gives a background of the rest molding which can be utilized for later designing a decentralized structure hierarchical adaptive sliding mode controller, position and attitude loops separated controllers can be designed to achieve desired trajectory tracking.

At the same time, reliable detection of such obstacles in real time constitutes a critical obstacle for safe navigation within cluttered environments. In this context, a better YOLOv8 object detection architecture is utilized. Standard YOLOv8 is a general-purpose algorithm that serves as a good trade-off between speed and detection performance but does not work well in UAV-based applications dominated by extreme scale variation of objects, degradation of features due to complex backgrounds, and the requirement of real-time processing on embedded platforms [7]. The proposed enhancement incorporates a multi-scale feature fusion approach and an attention mechanism. The multi-scale fusion helps understand objects with significant size difference — extremely helpful for urban scenarios like vehicles being far away from the cameras to pedestrians and vice versa. Attention mechanism is used to draw the network's attention toward salient regions where obstacles might exist, reducing noise caused by background cluttering and false positives. It is trained in aerial imagery datasets and further fine-tuned for detecting common dynamic obstacles such as vehicles, cyclists or other UAVs.

In the end, the detection outputs are not used in silo. A straightforward kinematic trajectory prediction module is coupled with the detector for proactive avoidance instead of reactive collision. For each dynamic obstacle detected, its current position and velocity (estimated from frame to frame) are employed to predict it in a short time horizon. The UAV state, the inner prediction above and a safety radius that is imposed in the form of a constraint space as an avoidance field which will describe any area (repulsive field) for the UAV to escape. This constraint space is a high level guidance input to the formation controller, indicating when and where an avoidance action needs to be taken. Low

latency is key for our perception system, from image to constraint space generation, as the control system needs data about a sufficiently fresh environment to fly quickly in neat urban settings. When integrated with the dynamic model, this real-time perception layer forms the full "sense-and-act" loop on which the adaptive cooperative control framework is developed.

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

After establishing an accurate system model in Section 2 and a real-time environmental perception, the core control architecture is introduced in this section. Its main contribution is the design of an adaptive sliding mode controller which treats trajectory tracking for each UAV separately and apply it into a distributed cooperative control framework where swarm can have collective formation.

Each UAV is designed using an adaptive sliding mode control (ASMC) method for individual flight controller. In essence, the main goal is to have both the actual position and velocity of the UAV converge towards a given reference trajectory (or any part of it, e.g. : based on a high level path planner or coming from a formation coordination algorithm) First, you define the sliding surface as some function of the tracking error between the desired state and real state (the dynamic itself). Next, we provide the formulation of the control law to drive the system states on this sliding surface in finite time and keep them in that state indefinitely. After reaching the sliding surface, these systems exhibit matched uncertainty and disturbance invariance in their dynamics, along with built-in robustness. But the major disadvantage of traditional sliding mode control is chattering, which refers to uncontrollable high frequency variations in the control signal resulting from a discontinuous or switching function. This chattering can put too much pressure on our actuators and lead to unstable flight. To overcome this, the controller has an adaptive mechanism. Rather than knowing a conservative upper bound for all types of disturbances, (which usually results in chattering), the adaptive law estimates the size of the lumped uncertainties on-line. This estimated bound is subsequently employed to tune the control gain adaptively. In this way, the gain is only enough to counteract the real disturbances each time by making a difference small more than zero which will help reducing unnecessary control action and making smoother output.

As per the decoupled system model, the control design is of hierarchical structure. Adaptive sliding mode controllers for the outer-loop position subsystem and inner-loop attitude subsystem are developed individually. While the position controller outputs the desired thrust and attitude commands to track a 3D position trajectory. The attitude controller then tracks these desired angles in order to generate the necessary motor torques. In this way, the resulting layered approach allows us to design the control for complex underactuated UAV dynamics. as shown in Figure 2.

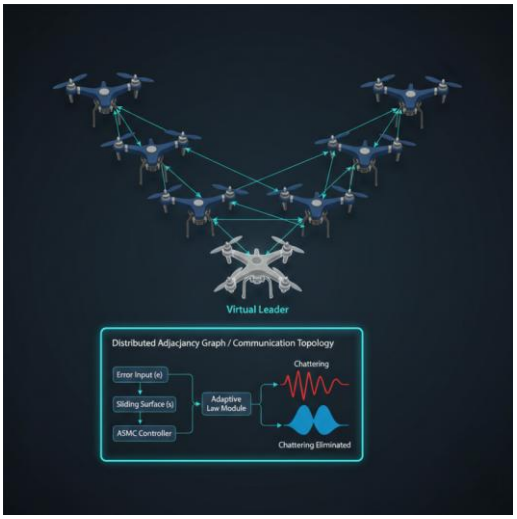


Figure 2. Perception & Obstacle Avoidance.

The ASMC serves as the necessary building block for swarm coordination by providing individual robustness. In order to have a formation flight between unbiased vehicles with r^ndom initial relative positions or velocities, the control strategy needs to be generalized to a decentralized cooperative strategy. This work utilizes a leader-follower structure based on the distributed consensus theory. The reference trajectory of the swarm is generated at a virtual leader Leaders in the follower UAV do not require direct communication with this leader. In contrast, communication is inherently localized through a fixed adjacency graph topology in which each UAV only communicates state information (e.g., position, velocity) with its direct neighbors in the formation graph. Then, the individual ASMC are combined with a consensus term to design a distributed cooperative control law. The consensus term is made up of the weighted difference between a UAV and its neighbours in state. This term serves to couple the physical motion of the UAV with its neighbors, drawing the format towards a common formation geometry defined as a function of the leader's path.

The last control input for each follower UAV can be decomposed into two parts, namely the part from its own adaptive sliding mode controller to ensure that the UAV accurately tracks its local desired trajectory and it term of consensus which is used to modify this desired behavior in order to maintain inter-Vehicle formation. This unified approach allows the swarm to perform cooperation tasks like formation keeping and reconfiguration whilst each UAV autonomously compensate local disturbances. This distributed strategy also improves the scalability and reliability of the system because if one communication link fails, it does not take down the entire swarm. The unique characteristic of flying ad hoc networks (FANETs) enables such dynamic topologies in a mobile fashion but also brings communication challenges which have been emphasized as vital for deploying it in real world [1]. The provided framework in this paper yields a reliable and resilient approach for UAV swarms to operate successfully in real applications such as smart cities, where the uninterrupted persistence of formation integrity during maneuvers is critical. 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 (dmin, 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

Our results provided an implementation of a cooperative survey in dense urban environment considering obstacle avoidance and formation control for multi-rotor UAVs. The main contribution is that it combines an upgraded real-time perception system and a distributed adaptive control framework. An enhanced visual detection and prediction algorithm was also used to create a space of dynamic constraints, enabling the swarm to derive knowledge in real-time about their environment. Based on this and environmental knowledge, a hierarchical control strategy was developed. On the individual scale, a novel adaptive sliding mode controller is proposed to guarantee accurate trajectory tracking while effectively suppressing the chattering phenomenon typical of classical schemes. It was then incorporated in a distributed leader-follower consensus scheme, wherein local neighbor-to-neighbor communication was used to guarantee that the swarm has the desired formation. It gives system a good robustness against model uncertainties and external disturbance due to this architecture.

The novel method was validated by detailed simulation and real flight experiments. The findings confirm that the UAV swarms navigate robustly through dense and dynamic obstacle fields, with a significant improvement in avoidance maneuver response time due to the integrated system. At the

same time, it prevents formation position errors from exceeding a very small range so that both safety of operation and relative location will be assured. The results show that this approach provides a technically feasible and realistic path for increasing the autonomy and reliability of UAV swarms in key application fields like urban logistics and emergency response.

First, even though the current perception system is strong, scaling it for more classes of different obstacle types and their intents in high redundancy scenarios will make decision making more efficient. Second, this work assumes a static and reliable communication topology. In future work, we will be testing new control strategies that are robust against dynamic communication delays, packet loss, and even intermittent link failures — ever present in real-time FANETs. Third, covering sophisticated swarm tasks involving splitting and merging of formations around large obstacles or collaborative manipulation is much more complex problem than what is presented in this work. The transformative step, however, will be to validate this research on the ground in relevant applications by executing large-scale experiments in real-world urban canyons subject to GNSS-denied environments and strong wind perturbations. These challenges must be overcome for Autonomous UAV Swarms to reach their full potential in future smart city ecosystems.

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