Spatiotemporal consistency cooperative control of multi-UAVs based on V-REP simulation

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Abstract. With the rapid development of UAV technology, the cooperative control of multi-UAVs system has become one of the research hotspots in UAV field. In this paper, the collaborative control of multiple UAVs in complex environment is studied to improve the performance of UAVS in terms of satisfying spatiotemporal consistency. Firstly, this paper introduces the basic principle and characteristics of V-REP simulation platform and its application advantages in multi-UAVs system simulation. Then, this paper proposes a spatiotemporal consistent cooperative control method for multi-UAVs based on V-REP simulation. Based on the information exchange between UAVs and the desired multi-mode formation, the formation and formation maintenance of UAVs are realized by using distributed control and multi-mode precision collaborative control technology, and the efficient cooperative movement of UAVs in complex environments is ensured. In order to verify the effectiveness of the proposed method, we conducted a series of experiments in a V-REP simulation environment. The experimental results show that the proposed method can effectively improve the spatio-temporal consistency performance of multi-UAV systems, and the completion rate of different tasks is above 90%, which has good applicability and robustness.

Keywords: UAVs simulation · UAVs communication · Spatiotemporal consistency · Cooperative control.

1 Introduction

In recent years, with its rapid development, UAV technology has penetrated many fields such as military, civil, and scientific research [1]. Especially in the fields of mission execution, disaster monitoring, resource exploration, etc., the application demand of UAVs shows an increasing trend. Its advantage is that it can quickly cover large areas, perform high-risk tasks, and carry a variety of sensors for data acquisition and processing. However, with the diversification of application scenarios and the complexity of mission requirements, the traditional single UAV system has been unable to meet the requirements in some cases [2]. Complex and changing environments and missions put higher demands on unmanned aircraft system, and the limitations of a single UAV are obvious. Therefore, the collaborative work of multiple unmanned aerial system is particularly important.

In multi-UAVs system, how to achieve spatiotemporal consistency collaborative control is a challenging problem [3]. Spatiotemporal consistency requires that multi-UAVs can maintain good formation and coordinated movement when performing tasks, and can respond to changes in the external environment in a timely and accurate manner. However, the complexity, uncertainty, and dynamics of multi-UAVs system bring great challenges to collaborative control.

In 1995, researchers such as Benjacob [4] analyzed the velocity-matching behavior in the Boid model and found that after a period of movement, the velocity, size, and direction of individuals in a cluster tend to be stable and consistent. In 2004, Olfat-Saber et al. [5] successfully summarized the communication topological relationship between UAVs into a network communication topological diagram by analyzing the problem of first-order dynamic models with time-delay and transformation topologies, which laid the foundation of consistency control theory. In 2005, W. en and Beard et al. [6] successfully proved that the network communication topology of a system with a spanning tree is a sufficient and necessary condition for the consistency problem of a first-order system to converge stably under a fixed topology. At the same time, the consistency problem under a switching topology was discussed and the necessary solution of the problem was given. In 2007, Olfat-Saber and Fax et al. [7] classified and summarized many problems related to consistency control algorithms, and analyzed in detail the formation problem, information consistency problem, performance problem of consistency controller and consistency convergence problem. In 2007, Xie et al. [8] solved the multi-agent formation problem of particle model based on Newtonian mechanics under the consistency control protocol by introducing a local velocity feedback device. In 2010, Wei and Cheng et al. [9] discussed the consistency problem of linear high-order multiple UAVs. In 2012, Jia and Tang et al. [10] studied the consistency problem of multi-agent system with time lag, delay, and topological transformation, and found that after the whole system reached consistency, some individuals lost communication with the cluster system, but the system could still maintain consistency and stability. In 2016, He and Li et al. [11] studied the consistency problem of higher-order nonlinear system with time lag and topological transformations under noisy environment and pointed out that the consistency problem under such conditions could be converted into the optimal solution problem for solving the response linear matrix. In 2017, Hernandez and Leon et al. [12] designed a formation control algorithm for a second-order system based on the piloted follower with time delay. The researchers used second-order sliding mode control to make each follower and the leader preset a distance, and successfully control the track of the tracking leader. This method not only eliminates the influence of time delay, but also ensures the system has good stability. In 2020, Belkacem Kada [13] proposed a new second-order nonlinear multi-agent system (MAS) distributed consensus algorithm, which provides smooth input signals for the control channel of the agent and avoids the flutter effect caused by traditional sliding mode-based control protocols. In 2023 Shraddha Barawkar [14] A new approach to collaborative transport (CT) missions using multiple quadcopter UAVs and using the leader-follower approach. These studies focus on the change of communication topology and communication time delay in multi-UAV systems, but these factors pose challenges to the consistency control, and it is necessary to design multi-mode precise cooperative control to ensure the stability and consistency of the system under these conditions.

This paper mainly studies and analyzes the spatiotemporal consistency cooperative control method of multi-UAVs based on V-REP simulation. The main contents of the study are as follows:

- V-REP simulation platform was used for modeling and simulation of multiple unmanned aerial systems to verify the effectiveness and performance of the collaborative control method.
- Distributed control and multi-mode precise cooperative control technology are proposed to improve the efficiency of UAV cluster facing fixed distributed group targets.

2 V-REP Simulation environment configuration

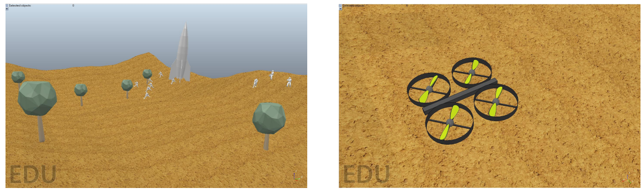
In this section, we describe how to configure a V-REP simulation environment for modeling, simulation, and validation of control algorithms for multiple unmanned aerial systems. V-REP [15] is a powerful simulation software that provides a wealth of modeling tools and physical simulation engines to meet the needs of multi-UAVs system simulation.

2.1 Scene modeling and UAV model import

In V-REP, users can model the scene through drag-and-drop operations or scripting. In the process of modeling, it is necessary to pay attention to keeping the rationality and authenticity of the scene, including terrain, obstacles, task objectives, etc. For terrain modeling, users can use the tools provided by V-REP to create flat or complex terrain and adjust the height and shape of the terrain according to the actual situation. This can be done by adding terrain objects to the scene and adjusting them using the editing tools, as shown in Fig. 1 (a). For the import of UAV models, V-REP provides a variety of UAV model libraries, and users can select appropriate models to import into simulation scenarios according to their needs, as shown in Fig. 1 (b).

2.2 Sensor Settings and environment parameter Settings

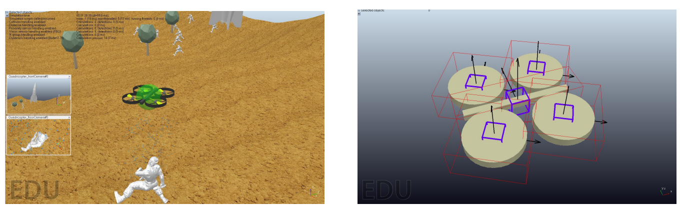
The simulation of multiple unmanned aerial system usually needs to consider the setting of sensors and the configuration of environmental parameters. In V-REP, we do this by setting various sensor parameters and adjusting environmental



(a) Scene modeling (b) UAV modeling

Fig. 1. Scene modeling and UAV model import.

parameters. For visual perception, we set camera parameters as resolution $1280*720$, field of view Angle $90°$, frame rate 30 $frames/s$, as shown in Fig. 2 (a). For the Lidar sensor, we can set the scanning Angle of the lidar to $360°$, the scanning speed to $10Hz$, and the scanning resolution to $0.1°$. For the Inertial Measurement Unit (IMU) sensor, we set the sampling frequency to $100Hz$, the gyroscope and accelerometer noise levels to 0.01 rad/s and 0.1 m/s^2, and zero bias to 0.1 rad/s and 0.5 m/s^2, as shown in Fig. 2 (b).



(a) Environment parameter Settings (b) Sensor Settings

Fig. 2. Sensor Settings and environment parameter Settings.

2.3 Control algorithm integration and simulation run

We can use the API interface provided by V-REP or custom scripts to integrate the designed control algorithm into the simulation scenario. The function of motion control, path planning and obstacle avoidance can be realized by writing the script. When integrating the control algorithm, it is necessary to ensure the good interaction between the algorithm and the simulation environment to ensure the accuracy and authenticity of the simulation.

2.4 Data recording and result analysis

In the process of simulation operation, we record various data in the simulation process through the data recording function provided by V-REP, such as UAV position, speed, attitude, etc. The recorded data is analyzed to evaluate the performance of the control algorithm and the validity of the simulation results.

3 Spatiotemporal consistency cooperative control algorithm

In multi-unmanned aerial vehicle system (UAVs), achieving spatiotemporal consistency of cooperative control is the key to ensure that UAVs can maintain good formation, coordinate movement and respond to external environment changes in time. This section will introduce spatiotemporal consistency cooperative control algorithms, including distributed control and four cooperative mode designs.

3.1 Distributed control

Distributed control is a formation method widely used in multi-UAVs system. Its core idea is that each UAV has an independent controller, which can adjust its own actions according to its own state and surrounding environment information, so as to achieve the formation goal, as shown in Fig. 3. This method does not require the involvement of the central controller, and each UAV adjusts its behavior by communicating with the surrounding UAVs, so the communication volume is low and the system has high stability and robustness. However, since the behavior of each UAV is relatively independent, it is often difficult to achieve the global optimal formation effect, mainly because of the spontaneity of the individual behavior of the UAV and the limitation of local information.

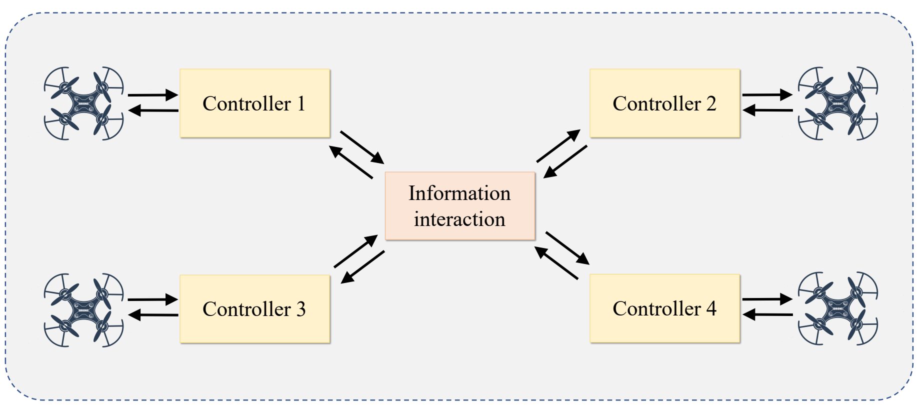


Fig. 3. Distributed control of multi-UAVs.

The behavior-based control algorithm used in this section is a typical implementation of distributed control. The algorithm makes a set of basic behavior rules for each UAV and considers the mutual influence of each UAV in formation to realize formation and maintenance of formation.

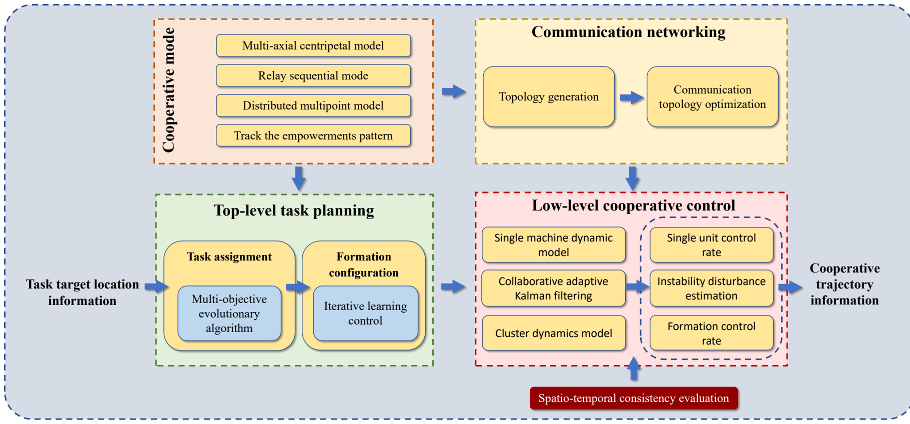


Fig. 4. Multi-UAVs cooperative mode design scheme.

3.2 Collaborative pattern design

In the collaborative mode design, the primary task is to design and optimize the multi-mode precise collaborative control technology to improve the efficiency of UAV clusters in the face of fixed distributed group targets. We present the specific control scheme in Fig. 4, and input the position information of mission targets into the top-level task planning for task assignment and formation configuration (four collaborative modes), as well as the overall trajectory generation. Then through the communication network and the bottom layer cooperative control, the formation coordination is realized.

First, we consider the task target location information as input. Then, we design four collaborative modes, which are multi-axial centripetal mode, relay sequential mode, distributed multipoint mode and tracking enhancement mode. These modes have different advantages in different scenarios.

Cooperative mode Multi-axial centripetal design. As shown in Fig. 5 (a), the development of this mode aims to ensure that the UAV cluster can achieve a multi-axis first flight arrival time interval of no more than 2 seconds when the number of centripetal axis is not less than 6, so as to form an efficient clustering capability. The control method is as follows.

$$F_{\text{centripetal}} = \sum_{i=1}^{N} m_i \cdot a_i \tag{1}$$

Where $F_{\text{centripetal}}$ represents the centripetal component of the resultant force, m_i represents the mass of the i^{th} UAV, and a_i represents the acceleration of the i^{th} UAV.

Relay sequential mode design. As shown in Fig. 5 (b), the main goal of this model is to ensure a high degree of coordination between adjacent UAVs in

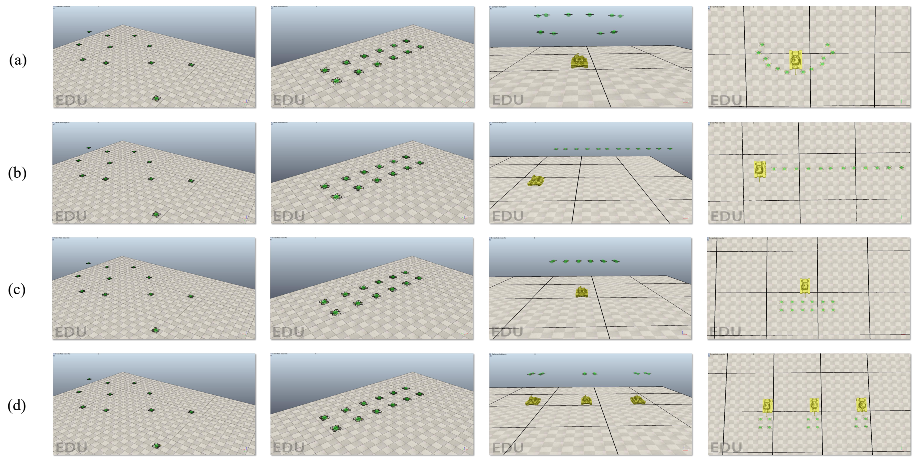


Fig. 5. Simulation diagram of four cooperative modes of multi-UAVs.

the time to reach the target, so that the cluster can achieve a coherent effect in the case of multiple target encounters. The control method is as follows.

$$R_{\text{sequence}} = \frac{1}{N}\sum_{i=1}^{N} R_i \tag{2}$$

Where R_{sequence} represents the average relay distance, and R_i represents the relay distance of the i^{th} UAV.

Parallel pattern design. As shown in Fig. 5 (c), the innovation of parallel mode aims to improve the coverage and effectiveness of the target by making the cluster collaborate on the target in parallel directions. The introduction of this mode not only enables the UAV cluster to collaborate more effectively, but also achieves an optimization in space utilization and improves the overall efficiency. The control method is as follows.

$$P_{\text{parallel}} = \frac{1}{N}\sum_{i=1}^{N} P_i \tag{3}$$

Where P_{parallel} represents the average distribution distance, and P_i represents the parallel distance of the i^{th} UAV.

Distributed multipoint model. As shown in Fig. 5 (d), this mode aims to achieve multi-UAVs covering and cooperating with multiple target points at the same time to improve the efficiency and coverage of task execution. In this mode, UAVs communicate and collaborate with each other to perform tasks at different target points, while maintaining a certain interval and coordination. The control method is as follows.

$$D_{\text{multipoint}} = \frac{1}{N}\sum_{i=1}^{N} D_i \tag{4}$$

Where $D_{\text{multipoint}}$ is the average distribution distance, and D_i represents the distribution distance of the i^{th} UAV.

Top-level task planning Top-level task planning mainly includes task assignment and formation configuration. For task assignment, this paper adopts a multi-objective evolutionary algorithm, whose mathematical form is as follows:

$$\operatorname{argmin}\left(\sum_{i=1}^{N} f_i(x)\right) \tag{5}$$

Where $f_i(x)$ represents the i^{th} objective function and x represents the decision variable. For the formation configuration, the iterative learning control method is adopted. Then, consider communication network establishment and optimization, including topology generation and communication topology optimization.

$$G = \{V, E\} \tag{6}$$

Where V represents the set of nodes and E represents the set of edges.

Low-level cooperative control The low level cooperative control strategy aims to realize the efficient cooperative operation of multiple unmanned aerial systems. The strategy consists of three key components: single-machine dynamic modeling and control, collaborative adaptive filtering and instability disturbance estimation, and formation control rate design.

First, we set up a single dynamic model for each UAV to describe its motion characteristics. The single machine dynamic model is expressed in the form of linear dynamic system.

$$\begin{cases} \dot{x}_i = A_i x_i + B_i u_i \\ y_i = C_i x_i \end{cases} \tag{7}$$

Where x_i represents the state vector of the i^{th} UAV, u_i represents the control input vector, y_i represents the output vector, and A_i, B_i, and C_i are the state transition matrix, input matrix, and output matrix respectively.

These dynamic models are used to calculate the control rate of each UAV. The control rate determines how each UAV responds to external commands and works in concert with other UAVs.

$$u_i(t) = K_i x_i(t) \tag{8}$$

Where $u_i(t)$ represents the control input of the i^{th} UAV, $x_i(t)$ represents the state vector of the i^{th} UAV, and K_i represents the control gain.

In order to estimate the system state more accurately, we introduce collaborative adaptive Kalman filtering technology to update the estimate of the system state in real time by combining the measurement data and dynamic model of each UAV.

$$\begin{cases} \hat{x}_{k|k} = A\hat{x}_{k-1|k-1} + Bu_{k-1} \\ P_{k|k} = AP_{k-1|k-1}A^T + Q \\ K_k = P_{k|k}C^T(CP_{k|k}C^T + R)^{-1} \\ \hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(y_k - C\hat{x}_{k|k-1}) \\ P_{k|k} = (I - K_kC)P_{k|k-1} \end{cases} \tag{9}$$

Where, $\hat{x}_{k|k}$ represents the state estimate at time k, $P_{k|k}$ represents the state covariance estimate at time k, K_k represents the Kalman gain at time k, Q represents the process noise covariance, and R represents the measurement noise covariance.

At the same time, we consider possible instability disturbances that may affect the motion stability of the UAV. By estimating and compensating for these disturbances, we improve the robustness and stability of the system.

$$\hat{d}(t) = \frac{1}{N}\sum_{i=1}^{N}\hat{d}_i(t) \tag{10}$$

Where $\hat{d}(t)$ represents the instability disturbance estimation at time t, and $\hat{d}_i(t)$ represents the instability disturbance estimation of the i^{th} UAV.

Next, these single-machine control strategies are extended to the entire cluster, taking into account the cluster dynamics model. Finally, the formation control rate is designed so that the whole UAV cluster can perform the task in a coordinated manner and maintain the formation form.

$$u_i(t) = K_f(e_i(t) - \dot{e}_i(t)) \tag{11}$$

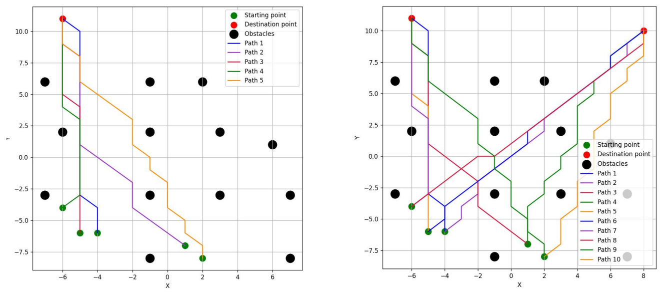
Where, $u_i(t)$ represents the control input of the i^{th} UAV, $e_i(t)$ represents the position error of the i^{th} UAV, $\dot{e}_i(t)$ represents the speed error of the i^{th} UAV, and K_f represents the formation control gain.

Finally, the spatial-time consistency evaluation is carried out, and the collaborative trajectory information is output, and the design scheme of multi-UAV collaborative mode is realized.

4 Spatiotemporal consistency experiment

In the spatio-temporal consistency experiment, we will establish the corresponding simulation scene in the V-REP simulation platform according to the given multi-UAV road map, and configure the initial position, speed, mission target and other parameters of the UAV. Then, by performing a series of tasks, the collaborative performance of multiple unmanned aerial systems in time and space is evaluated.

According to the experimental data and performance evaluation indicators in Fig. 6 and Table 1, the spatiotemporal consistency performance of multiple unmanned aerial system when executing different tasks and adopting different control strategies is analyzed. The average formation spacing is less than 10



(a) Simple target (b) Multiple targets

Fig. 6. Multi-UAVs spatiotemporal consistency experimental route.

meters, and the formation shape change rate is less than 0.5 degrees/s, indicating that the formation maintains a high stability. The average task execution time is 100 seconds, and the average task completion rate is over 90%.

Table 1. Spatiotemporal consistency of multi-UAVs.

Cooperative mode	Interval (m)	Rate ($°/s$)	Time (s)	Completion
Multi-axial centripetal	10	0.55	110	95%
Relay sequential	6	0.52	120	90%
Parallel	8	0.53	110	95%
Distributed multipoint	15	0.60	115	94%

5 Conclusion

In this paper, the collaborative control of multiple unmanned aerial vehicles (UAVs) is studied, and a spatiotemporal consistency collaborative control method based on V-REP simulation is proposed. Through distributed control and multiple cooperative mode design, combining the concept of information exchange and multi-mode formation, the formation and formation maintenance of UAV formation mode are effectively realized, while ensuring efficient cooperative movement in complex environments. Through a series of experiments in V-REP simulation environment, the effectiveness of the proposed method is verified. Experimental results show that the proposed method can significantly improve the spatiotemporal consistency performance of multi-UAVs system, and has good applicability and robustness.

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