UAV Formation Control Method Based on Consistency Strategy

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Abstract. Based on a Four-rotor UAV model, a distributed UAV cooperative formation control algorithm based on consistency strategy in three-dimensional space is proposed. The convergence and validity of the proposed algorithm are proved by simulation experiments under the condition that the model and simulation assumptions are satisfied.

1. Introduction

When a single UAV carries out large and complex tasks, its efficiency is low and its success rate is low. From the point of view of time, single UAV has a shorter duration. For some complex tasks requiring large-scale search (such as natural disaster patrol and in-depth rescue and relief), its maximum travel will be limited; from the point of view of space, the activity radius of single UAV is limited, which will seriously reduce the task of large-scale military reconnaissance mission. Completion efficiency; from the mission level, the anti-jamming ability of single UAV is weak, detection ability and load capacity are limited, which will increase the probability of mission failure. In contrast, cooperative formation of multiple UAVs can solve conflicts at the time, space and mission levels. When the task is complex and the flight area is large, the total task can be divided into some simple small tasks. Each UAV carries different detection equipment to complete its own tasks, so that the total task can be completed at one time, thus significantly improving the efficiency of the task.

Overall, the advantages of cooperative formation of multiple UAVs lie in the following points: (1) it can realize large field of vision reconnaissance, high precision positioning and multi-angle imaging. (2) It can improve the success rate of task execution and the overall hit rate. (3) It can prolong the duration and reduce the overall flight resistance.

In the formation control of UAV with virtual leader, the traditional master-slave centralized control method needs a lot of information exchange, which requires high communication requirements, large computation and complex algorithm. In distributed UAV formation, UAV determines its own motion state according to the state of the surrounding UAV that it can detect, thus forming formation and arriving at its destination independently.
2. Multi-UAV Cooperative Formation Control

2.1. Formation Control Mode of UAV

The research of UAV formation control was originally aimed at its application in spacecraft. Since the 21st century, formation control for UAV has been widely studied. In the communication mechanism, UAV formation control can be divided into three main types:

- Centralized control: Each UAV must communicate the position information of attitude, velocity and position to all other single aircraft, and each single aircraft knows all the information of formation. In this way, the control difficulty is the least and the accuracy is the highest, but the computational performance and communication bandwidth requirements are high.
- Decentralized control: Each UAV only knows its target point in formation and does not communicate with other UAVs. This formation method is simple in structure and easy to implement, and has the worst adaptability and robustness to the environment.
- Distributed control: Each UAV only communicates with its neighbor UAVs. The control effect is slightly worse than centralized control, but the requirement of communication bandwidth is greatly reduced and the realization is simple. Distributed control needs less information and avoids collision. It is convenient for engineering realization. In addition, distributed control has certain advantages in the weight and separation of formation. It can limit the impact to a local scope and is the future development direction of formation information interaction.

Formation control refers to the control technology of how to form and maintain a certain geometric configuration in order to meet the requirements of platform performance, battlefield environment, and tactical tasks and so on. The formation control of multiple UAVs mainly solves the following two problems: first, formation formation formation formation formation/reconfiguration, including formation generation before flight, formation splitting and reconstruction when encountering obstacles, and formation reconfiguration when increasing or reducing UAVs; second, formation maintenance, including formation maintenance in flight, in different geometries. Formation switching between states, formation shrinkage, expansion and rotation control under the condition of keeping geometric shape unchanged, etc.

2.2. Formation Control Method of Multi-UAV

The main methods are Leader-Follower, Virtual Leader and Behavior Control. [4]

- Leader-Follower. The general maintenance strategy is to keep the relative position of each UAV in the formation unchanged with the agreed point in the formation. When the agreed point is the pilot aircraft, this maintenance strategy is called follow-up maintenance. Pilotage-following is a kind of following and keeping. The characteristic of this control strategy is based on the preset formation structure. By tracking the speed, yaw angle and altitude of the long aircraft, the wingman can be adjusted to maintain the formation. Long-machine-bureau method is the oldest formation control method. Its principle is simple and easy to implement, but its robustness is slightly poor, and the error will propagate backward step by step and be amplified. This control structure will be greatly affected by interference. In view of its characteristics, many researchers have improved this control strategy by combining robust control method, extremum search control method, scroll adjustment technology, adaptive control method and variable structure control method. But after using these methods, the shortcomings of pilotage-following method are also obvious, that is, the position of all UAVs must be recalculated after emergencies, which increases the burden of computers.

- Virtual Leader. The virtual Leader method proposed by the University of West Virginia is characterized by keeping a specific geometric shape between UAVs, which is similar to a virtual structure of rigid bodies. Each single aircraft maintains its formation through different points on rigid bodies. The method can be divided into three steps: firstly, the expected dynamic model of virtual rigid body is established, secondly, the expected dynamic model is transformed into the expected motion constraints of each single machine, and finally, the formation control strategy of each single machine is obtained. The virtual Leader method simulates the formation as a virtual rigid body geometric shape.
The formation control is carried out through fixed points on the rigid body, which is relatively simple to realize and can obtain higher formation control accuracy. However, due to the expectation that the formation is a rigid body, the method cannot meet the control requirements when the formation transformation, separation and combination are needed, and it lacks flexibility and adaptability.

Behavior control. During the formation flight of multiple UAVs, the behavior response of each UAV in the cluster to the input information of its sensors may have some situations: collision avoidance, obstacle avoidance, and target acquisition and formation preservation. The most important feature of this method is to determine which behavior response mode each UAV should adopt in formation by means of the average weight of behavior response control. Cao Zhiqiang et al. used genetic algorithm to determine the weight of control in order to select appropriate behavior response to maintain formation and avoid obstacles. Behavior control method is a kind of formation control method which simulates biological reaction behavior mechanism. It has good flexibility and robustness, but it cannot achieve accurate formation maintenance, and it is difficult to analyze the stability of the system by mathematical method.

Formation control of multi-UAV is an interdisciplinary field involving control, navigation, computer, communication, artificial intelligence, aerodynamics and other disciplines. Although a series of progress has been made in the field of formation control in recent years, there is still a certain distance from the actual engineering application. The main problems at present are: (1) Unmanned aerial vehicle (UAV) modeling is not accurate enough and the aerodynamic model of UAV is simplified to a great extent, which restricts the performance of formation controller. (2) Most formation control uses the Leader-follower method. In fact, it only follows the bureau. Once the leader breaks down, the follower will fail immediately. (3) The quality of communication seriously restricts the performance of formation control algorithm. When the communication between UAVs is lost and delayed, the effect of the controller will become worse.

3. UAV formation control algorithm based on consistency strategy

3.1. Information Consistency Theory
In 1986, Professor Munsky of MIT's Laboratory of Artificial Intelligence first proposed the concept of Agent. Multi-Agent System is a group of autonomous agents. Many agents share their knowledge, goals, strategies and plans through information exchange. Multi-agent system is an important branch of distributed artificial intelligence, and it is the frontier subject of artificial intelligence in the world at the end of the 20th century and the beginning of the 21st century. The purpose of this research is to solve large and complex practical problems, which are beyond the capability of a single agent.

Information Consensus enables each agent's state or goal to achieve consistency through interaction. Information consistency is an excellent intelligent control strategy, which has a wide range of applications in many fields, such as UAV formation control, satellite formation control and so on. For UAV formation, each UAV is regarded as an agent, and the whole formation is a multi-agent system. The communication data between UAVs constitute the information flow together. The basic task of multi-agent consistency theory is to use consistency control strategy to generate consistent common output for swarm systems based on the input information that may conflict with multiple agents, and theoretically prove that the upper bound and the next round of rounds required to achieve consistency are the same.

There are many formation algorithms for UAV. In this paper, a multi-agent control algorithm based on information consistency is adopted. Consistency is a basic problem in multi-agent collaborative control. By communicating data among agents to form information flow, the errors of each agent relative to other agents can be obtained. By controlling the errors, the states of all agents can be kept consistent.

3.2. Dynamics Model of Four-Rotor Unmanned Aerial Vehicle
The dynamic model of a four-rotor UAV is expressed as follows:
The Euler angles of the three attitudes of the aircraft are expressed as \( [\varphi, \theta, \psi] \), representing the roll angle, pitch angle, and yaw angle, respectively. The position coordinates of the mass center of an aircraft in the inertial coordinate system represent \([x, y, z]\), the radius length \( l \) of the aircraft represents the distance from the end of each rotor to the center of gravity of the aircraft, \( m \) represents the total mass of a Four-rotor UAV, \( I_i \) represents the moment of inertia around each axis, and \( K_i \) represents the drag coefficient.

The control objective is to take the actual linear velocity \( \mathbf{v} = [\mathbf{x}, \mathbf{y}, \mathbf{z}]^T \). The expected speed of a given virtual pilot is \( \mathbf{v}_d \). The control tasks are linear velocity and attitude control. The control rate \( u_1 \) is designed to track the desired tracking speed and roll angle \( \varphi \), and to follow the angle of \( \theta \) and \( \psi \).

The communication between UAVs is bidirectional. In the process of formation flying of multiple UAVs, two-way communication is conducive to UAV formation cooperative flying to complete various tasks. At the same time, when the number of UAVs in formation expands to more than three, the stability and reliability can be improved. The two-way network topology of UAV formation is shown in the Fig.1.

![Figure 1. Two-way Network Topology of UAV Formation](image)

3.3. **UAV formation control algorithm based on consistency strategy**

The control of synergetic variables is the core content of consistency theory [5], and synergetic variables have great advantages in practical application. For example, in the battlefield environment, a single UAV is destroyed with only one set of synergistic variables missing. Other UAVs continue to rely on the remaining synergetic variables to achieve information consistency, which will not affect formation control. When the formation does not reach a stable state, the position synergetic variables generated by each UAV are different. The purpose of the synergy control is to make the position synergy variables coincide eventually, so as to achieve the asymptotic consistency and stability of the formation position. When all the synergetic variables are consistent, the formation position stability and attitude synchronization are achieved, and the formation stability is maintained.

The formation control of multi-UAV consists of two parts, cooperative flight control system and cooperative track control system. The cooperative flight control system is an inner loop, which controls flight attitude; the cooperative track control system is an outer loop, which controls flight trajectory, and the output of the outer loop is the input of the inner loop. The cooperative flight path control system
calculates the corresponding flight path commands such as pitch angle, yaw angle and speed according to the scheduled flight path, and then transmits them to the cooperative flight control system. After receiving the command, the flight control system tracks the track control command by calculating the control rudder deflection. If no route is set in advance, the formation can fly freely, and the task of track control will become simpler, only cooperative flight control is needed. In formation cooperative control of UAV, a feedback control law based on information consistency algorithm is designed to achieve formation maintenance and attitude coordination tasks.

The control system structure of each UAV is shown in the fig. 2. In order to control UAV formation flying according to expected trajectory, two control schemes of compatible inner and outer loop control are proposed. The main task of outer loop is to control the position, forward speed and expected trajectory of each UAV. Based on the control command generated by the outer loop, the inner loop receives the command to generate rudder deflection, and the aileron command controls the attitude system.

![Figure 2. The control system structure of UAV](image)

In order to achieve the control objectives, the speed control subsystem is designed to obtain the required time-varying thrust magnitude and direction, and the required attitude information is transmitted to the attitude control subsystem for tracking. Then Lyapunov stability analysis is carried out.

For the jth UAV, define:

\[
\begin{align*}
    u_{j1x} &= u_{j1x}(\cos \phi_j \sin \theta_j \cos \psi_j + \sin \phi_j \sin \psi_j) \\
    u_{j1y} &= u_{j1y}(\sin \phi_j \sin \theta_j \cos \psi_j - \cos \phi_j \sin \psi_j) \\
    u_{j1z} &= u_{j1z} \cos \phi_j \cos \psi_j
\end{align*}
\]  

To describe the jth UAV model:

\[
\begin{align*}
    \dot{x}_j &= u_{j1x} - \frac{K_s}{m} \dot{x}_j \\
    \dot{y}_j &= u_{j1y} - \frac{K_s}{m} \dot{y}_j \\
    \dot{z}_j &= u_{j1z} - g - \frac{K_s}{m} \dot{z}_j
\end{align*}
\]  

The expected position relationship between j and k of any two UAVs is delta \(\delta_{jk}\), the velocity of the j UAV is \(v_j\), and the velocity tracking error is \(\bar{v}_j = v_j - v_{id}\).

Control objectives are \(\bar{v}_j \rightarrow 0, p_j - p_k \rightarrow \delta_{jk}\). For the jth UAV, take \(P_j = [x_j y_j z_j]^T, U_j = [u_{j1x} u_{j1y} u_{j1z}]^T\), The jth UAV model \(\bar{p}_j = U_{j1} + [-\frac{K_s}{m} \dot{x}_j - \frac{K_s}{m} \dot{y}_j - \frac{K_s}{m} \dot{z}_j]^T - [0 \ 0 \ g]^T\)
Design Control Rate:

\[ U_{j1} = -\ddot{z}_j + \ddot{\theta}_d + \left[ \frac{K_1}{m} \ddot{x}_j \quad \frac{K_2}{m} \ddot{y}_j \quad \frac{K_3}{m} \ddot{z}_j \right]^T + [0 \ 0 \ g]^T - 2 \sum_{k=1}^{n} (P_{jk} - \delta_{jk}) \]  

(4)

The Lyapunov function is designed as follow:

\[ V = \frac{1}{2} \sum_{j=1}^{n} \ddot{z}_j^2 + \frac{1}{2} \sum_{j=1}^{n} \sum_{k=1}^{n} (P_{jk} - \delta_{jk})^2 \]  

(5)

Speed control:

\[ u_{j1} = \frac{u_{j1z}}{\cos \phi_j \cos \psi_{jd}} \]  

(6)

4. Simulation and Analysis

Take \( m=2, l=0.2, g=9.8, K_1=0.01, K_2=0.01, K_3=0.01, K_4=0.012, K_5=0.012, K_6=0.012, I_1=1.25, I_2=1.25, I_3=2.5 \). Three unmanned mechanisms are used to form a formation. The stability of the closed-loop system is guaranteed by adopting the method that the convergence speed of the inner loop is faster than that of the outer loop. The simulation time is 30 seconds, and the flight condition of UAV formation is checked at 14 seconds and 27 seconds.

![Figure 3. Velocity Convergence Process of the First UAV](image1)

![Figure 4. Velocity Convergence Process of the Second UAV](image2)
The simulation results show that the distributed formation control algorithm based on the above consistency strategy and the UAV model can make the UAV follow the virtual pilot trajectory and form a stable formation between the UAVs. The validity and rationality of formation control algorithm and UAV model based on consistency strategy are verified.

5. Summary and Prospect
In this paper, a non-linear UAV formation model is established, and a cooperative control formation algorithm for UAV formation in three-dimensional space is proposed. The convergence and validity of the proposed algorithm are proved by simulation experiments under the condition that the model and simulation assumptions are satisfied. This paper is only a theoretical study, not a physical test of UAV, but the physical test involves a large number of uncontrollable factors. Therefore, the application of this algorithm to formation controller in engineering practice is the next main research topic.

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