Leader-Follower Formation Control of Unmanned Aerial Vehicles Based on Active Disturbances Rejection Control

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ABSTRACT

Cooperative flight of multiple unmanned aerial vehicles (UAVs) has many advantages, but there are also some problems to be solved. This paper investigates the formation keeping and transformation problem by using the virtual leader-follower method. Firstly, for the multi-UAV system composed of particle models, the active disturbance rejection control (ADRC) method is adopted to design the formation keeping controller. Secondly, in order to prevent UAVs from crashing into each other during formation switching, the concept of virtual repulsion is introduced for collision avoidance. Then, to test the proposed formation keeping and transformation control method, a multi-quadrotor coordination simulation platform is constructed. The simulation results show the proposed method is effective.

CCS CONCEPTS

• **Computing methodologies→Control methods; Multi-agent systems;** • **Computer systems organization→**Robotic control

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KEYWORDS

Virtual leader-follower, Active disturbance rejection control, Formation keeping, Formation transformation

1 INTRODUCTION

Formation control is the basis for multiple UAVs to execute tasks. In recent decades, the application of UAVs in military and civil fields has been increasingly extensive, and formation control has also achieved breakthroughs and innovations continuously.

There are many advantages in multi-UAV collaborative formation flight. For example, it can shorten the task execution period, improve the performance and perform various tasks in complex or restricted environment, such as reconnaissance, attack, and rescue. Therefore, the work of multi-UAV formation control has aroused great attention[1-3]. However, UAV formation flight is a complex task, which faces many problems that need to be solved in theory and engineering, including reasonable UAV formation configuration design, real-time online formation adjustment, obstacle avoidance, communication, data fusion issues, etc[4]. This paper mainly studies the formation keeping and transformation strategy of quadrotor formation.

In existing literatures, the common methods of UAV formation control mainly include the behavior-based method, leader-follower method, virtual structure method, etc[5]. And among these methods, the leader-follower method is widely used.

In the problem of four-rotor UAV formation control based on (virtual) leader-follower method, many control algorithms have been successfully used, such as PID, sliding mode variable structure, adaptive control, backstepping control, etc. In [6], the feedback linearization method is adopted to form the formation, and a nonlinear estimator is also designed in view of the movement of the leader is uncertain. The stability of the controller–estimator combination is verified. In [7], in order to enable followers to keep up with the leader more quickly, an error mixer is added to the PID controller to maintain the formation. While in [8], to realize trajectory tracking control, linear quadratic regulator (LQR) and sliding mode control (SMC) are combined for a leader-follower formation. Considering the latent collision danger and potential actuator faults, [9] proposes an internal and external loop control method with the inner adaptive fault-tolerant control (FTC) and the outer leader-follower control. In literature [10], it proposes a novel structure for four-rotor UAV leader-follower formation control and a new control law using neural network (NN) to guarantee that all followers can track their leader with unmodeled dynamics. In [11], on the basis of virtual leader-follower structure, a new distributed cascaded robust tracking control method is adopted for the formation reconstruction control of vertical takeoff and landing UAVs. Literature [12] studies the problem of UAV leader-follower formation control in a three-dimensional space, and achieves good results through fuzzy logic control. Towards the application, the wind disturbance and the modeling inaccuracy are inevitable, and few works investigated the formation keeping and transformation problem in such cases.

Based on the virtual leader-follower configuration, this paper designs a formation keeping and transformation controller by using the active disturbances rejection control (ADRC) theory composing of the virtual repulsion, which is a practical nonlinear control method by using the simple integral series system as the standard form. The part of the system dynamics different from the normalized form is considered to be the total disturbance, which can be estimated and compensated by the extended observer in real time [13]. And nonlinear error feedback is applied in view of fast convergence of the error in order to achieve good control characteristics[14-16]. Therefore, the ADRC method, which has a simple structure, strong robustness and high engineering practicability, is very suitable for the quadrotor UAV system as there is no need for accurate modeling of the system or disturbance.

The main structure of this article is as follows: First, for solving the formation flight control problem, section 2 employs the ADRC method to design the formation keeping controller on the basis of virtual leader-follower formation control strategy. Then section 3 introduces virtual repulsive force to solve the possible collision problem among UAVs during formation transformation. While in section 4, based on Gazebo simulator, a multi-UAV collaborative simulation environment[17] is built, which can easily test and verify the feasibility and effectiveness of our collaborative algorithms.

2 VIRTUAL LEADER-FOLLOWER FORMATION KEEPING CONTROL

2.1 Problem Formulation

Suppose a formation consisting of N quadrotor UAVs, in which the particle model of the i-th quadrotor is:

$$\dot{x}_i = v_i \tag{1}$$

where x_i is the position and v_i is the velocity. The particle model is essentially a single integrator model, which can be used to approximate the description of the four-rotor UAV when the speed and attitude are under stable control.

The formation flight control system includes a formation keeping control subsystem and a trajectory tracking control subsystem. In this paper, the single UAV trajectory tracking problem is not discussed. By establishing the relative kinematic equations among the quadrotors, and designing the formation keeping controller, the formation can be maintained. Figure 1 shows the control diagram of formation keeping based on virtual leader-follower structure.

Here, all the UAVs in the formation are designed as followers, while the leader is designed as a virtual point related to the formation.

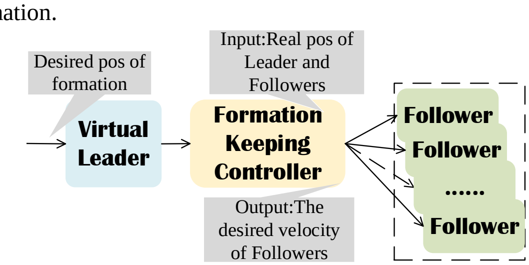

Figure 1: Schematic diagram of L-F formation control.

We define $\{v_{xi}, v_{yi}, v_{zi}\}$ as the speed of the i-th four-rotor UAV in its body coordinate system, and the combined velocity of v_{xi} and v_{yi} in the body coordinate system as v_i. The orientation angle ψ_i is that between v_i and the X-axis in the inertial system. The real-time position of each quadrotor can be uniquely determined by its velocity and orientation angle. To simplify the problem in actual analysis, we first assume that the orientation angle of each quadrotor UAV is $\psi_i \to 0$, that is, without considering the coordinate system conversion problem, it can be directly analyzed in the inertial system. Taking the two-quadrotor UAV case as an example, the relative motion relationship in the horizontal plane in the inertial system is shown in Figure 2.

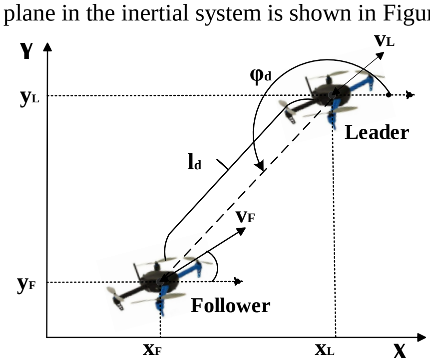

Figure 2: The relative motion relationship in horizontal plane.

Based on the virtual leader-follower method, the desired position $\{x_{Fd}, y_{Fd}, z_{Fd}\}$ of each follower can be determined by the actual position $\{x_L, y_L, z_L\}$ of the virtual leader and their expected distance l_d and angle φ_d as:

$$\begin{cases} x_{Fd} = x_L + l_d \cos\varphi_d \\ y_{Fd} = y_L + l_d \sin\varphi_d \\ z_{Fd} = z_L \end{cases} \tag{2}$$

Then, in subsection 2.3, the formation keeping controller can obtain the desired velocity commands for the followers by using such position information.

2.2 General First-Order Auto Disturbance Rejection Controller

For the particle model (1) of each quadrotor UAV, a general first-order auto disturbance rejection controller is designed. Assume that the common first-order controlled system is:

$$\begin{cases} \dot{x}_1 = f(t) + bu \\ y = x_1 \end{cases} \tag{3}$$

where $f(t)$ is the total disturbance, x_1 is the state variable, u is the control quantity, and b is the coefficient of u .

2.2.1 Extended State Observer (ESO)[15]. Extending the total disturbance $f(t)$ to a new state variable x_2, the original system (3) becomes:

$$\begin{cases} \dot{x}_1 = f(t) + bu \\ \dot{x}_2 = \dot{f}(t) \\ y = x_1 \end{cases} \tag{4}$$

Establish a linear extended state observer (LESO) for the system:

$$\begin{cases} \varepsilon = z_1 - x_1 \\ \dot{z}_1 = z_2 - \beta_1\varepsilon + bu \\ \dot{z}_2 = -\beta_2\varepsilon \end{cases} \tag{5}$$

According to (4) and (5), each state can be measured by the LESO as:

$$\begin{cases} z_1(s) = x_1(s) - \frac{s}{s^2+\beta_1 s+\beta_2} x_2(s) \\ z_2(s) = \frac{\beta_2}{s^2+\beta_1 s+\beta_2} x_2(s) \end{cases} \tag{6}$$

In order to ensure certain estimation accuracy, it is necessary to select a relatively large gain, that is, the coefficient β_1, β_2 should be larger and satisfies $\beta_1 < \beta_2$. In this way, the observation of state variables in the original system can be obtained, that is:

$$z_1 \to x_1, z_2 \to x_2 \tag{7}$$

2.2.2 Nonlinear State Error Feedback (NLSEF) Control[16]. For the original system (3), a nonlinear error feedback design can transform the system into a single integrator model:

$$\begin{cases} \dot{x}_1 = u_0 \\ y = x_1 \end{cases} \tag{8}$$

where,

$$u_0 = f(t) + bu \tag{9}$$

For a given reference signal v, we define the tracking error $e = v - y = v - x_1$, where x_1 can be replaced by z_1. Here, z_1 can be estimated by the state observer and the error state equation of the system is:

$$\dot{e} = \dot{v} - \dot{x}_1 = \dot{v} - u_0 \tag{10}$$

Non-smooth feedback is adopted as the NLSEF control law, according to which the system is expected to perform error convergence:

$$\dot{e} = -m \cdot fal(e, \alpha, \delta) \tag{11}$$

Then,

$$u_0 = \dot{v} + m \cdot fal(e, \alpha, \delta) \tag{12}$$

where,

$$fal = \begin{cases} e / \delta^{1-\alpha} \\ |e|^{\alpha} \operatorname{sgn}(e) \end{cases} \tag{13}$$

and m is the control gain, $\alpha (0 < \alpha < 1)$ is the nonlinear exponent, and δ is the linear range near the equilibrium point. According to (10) and (12), the control quantity u is:

$$u = \frac{u_0 - f(t)}{b} = \frac{m \cdot fal(e, \alpha, \delta) + \dot{v} - f(t)}{b} \tag{14}$$

where the disturbance $f(t)$ is estimated as z_2 by ESO, and it actually needs tracking differentiator to estimate $\dot{v}$.

2.2.3 Tracking Differentiator (TD). In literature [18], in order to meet the requirements of numerical calculation, Han Jingqing proposes the optimal control synthesis function $fhan(v_1, v_2, r, h)$. And the discrete speed feedback system established by this function is as follows:

$$\begin{cases} fh = fhan(v_1(k) - v(k), v_2(k), r, h_0) \\ v_1(k+1) = v_1(k) + h \cdot v_2(k) \\ v_2(k+1) = v_2(k) + h \cdot fh \end{cases} \tag{15}$$

where v is the given reference signal, v_1 and v_2 are system state variables, r is the fast factor, h is the sampling period, and h_0, other than h , can reduce the noise amplification effect.

By this feedback system, v_1 can keep up with the input signal v fast without overshoot, while the differential signal $\dot{v}$ can be tracked by v_2, which is the approximate differential of v_1.

2.2.4 General First-Order ADRC. By combining the above three modules (TD, ESO and NLSEF), a general first-order ADRC can be obtained[18]. Its basic structure is shown in Figure 3.

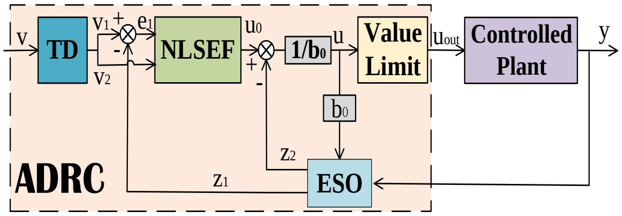

Figure 3: Basic structure of the first-order ADRC.

In practical applications, the output control quantity u should be limited, and the actual control quantity after limiting is:

$$u_{out} = \begin{cases} u & |u| < u_{\max} \\ u_{\max} \cdot \operatorname{sgn}(u) & |u| \geq u_{\max} \end{cases} \tag{16}$$

2.3 The Formation Keeping System Based on the First-Order ADRC

The formation keeping system (as shown in figure 4) is built by using the designed ADRC method, while the three-direction channels of the four-rotor UAV are decoupled.

Here, on the basis of the particle model (1), the controllers of the three-direction channels X-Y-Z of each quadrotor are all designed according to the first-order general ADRC method given in subsection 2.2.

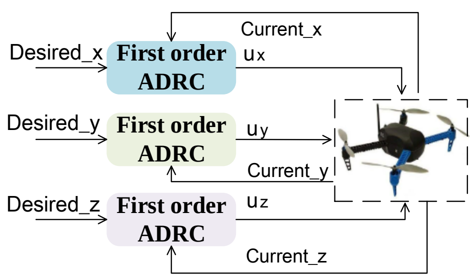

Figure 4: The formation keeping system based on the first-order ADRC.

3 MULTI-UAV FORMATION TRANSFORMATION AND COLLISION AVOIDANCE

In actual task execution, the multi-UAV formation should be adapted to the changes in the environment and missions, which requires transformation of the UAV formation.

3.1 Formation Design

On the basis of virtual leader-follower structure, this paper includes row, column, triangle and wedge formations, which are shown in Figure 5.

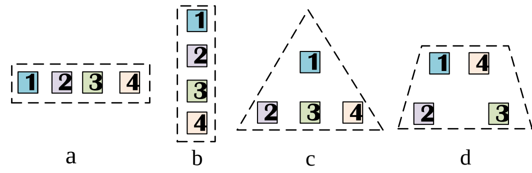

Figure 5: A simple schematic diagram of the four formations

We can change the UAV formation to satisfy our needs according to the designed formations.

3.2 The Formation Transformation Strategy

It is assumed that when the formation changes, the flight height of each quadrotor in the formation is consistent, and only the situation in the horizontal plane needs to be considered.

If the desired speed command for each quadrotor is only given in accordance with the formation keeping controller designed in subsection 2.3, that is, it is only determined by its position information. Here, we record this speed command as v_{pos} .

In this case, before reaching the respective target positions, each quadrotor flies according to its own speed command, and their flight trajectories may overlap each other at the same time, thereby causing collision.

To solve the potential collision problem among UAVs during formation transformation, the virtual repulsive force is introduced. Set the safety distance among quadrotor UAVs, and when the distance between any two quadrotor UAVs is shorter than the safety distance, a repulsive force is generated to separate them from each other.

Define the repulsion between any two quadrotor UAVs as:

$$f_{ij} = \begin{cases} \dfrac{(\|\vec{l}_{ij}\| - \mathrm{L}_{safe})\vec{l}_{ij}}{\|\vec{l}_{ij}\|} & if \left\|\vec{l}_{ij}\right\| < \mathrm{L}_{safe} \\ 0 & if \left\|\vec{l}_{ij}\right\| \geq \mathrm{L}_{safe} \end{cases} \tag{17}$$

where, L_{safe} is the set safety distance between two quadrotors, f_{ij} is the repulsive force of the i -th quadrotor generated by the influence of the j -th quadrotor, and $\vec{l}_{ij}$ is the distance vector between the i -th and the j -th quadrotor.

According to the main idea of speed control in this paper, the repulsion between two UAVs is multiplied by the appropriate coefficient as part of the speed command. For the i -th quadrotor, the sum of the speed commands generated by the repulsion of all remaining UAVs is denoted as $v_{repulsion}$,

$$v_{repulsion} = G \cdot \sum f_{ij} \quad (i \neq j) \tag{18}$$

Where G is the repulsion coefficient, and the desired velocity control command for each quadrotor after introducing virtual repulsion constraint is:

$$v_{Fd} = v_{pos} + v_{repulsion} \tag{19}$$

consisting of the speed command derived from position information and the speed command generated by the repulsive force.

4 SIMULATTON EXPERIMENT

To verify that the proposed formation keeping and changing strategies are effective, a multi-quadrotor coordination simulation platform is built based on Gazebo simulator and the robot operating system (ROS). Figure 6 is a schematic diagram of the simulation environment. Iris quadrotor model in Gazebo and PX4 open source autopilot are adopted.

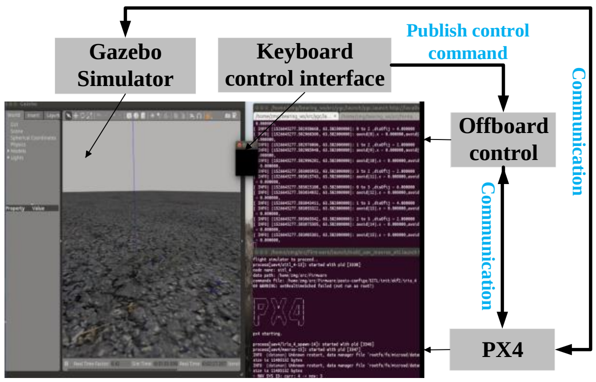

Figure 6: A schematic diagram of the simulation environment

4.1 Simulation Experiment for Formation Keeping Control

To verify the designed formation keeping control method, the following experiments are carried out.

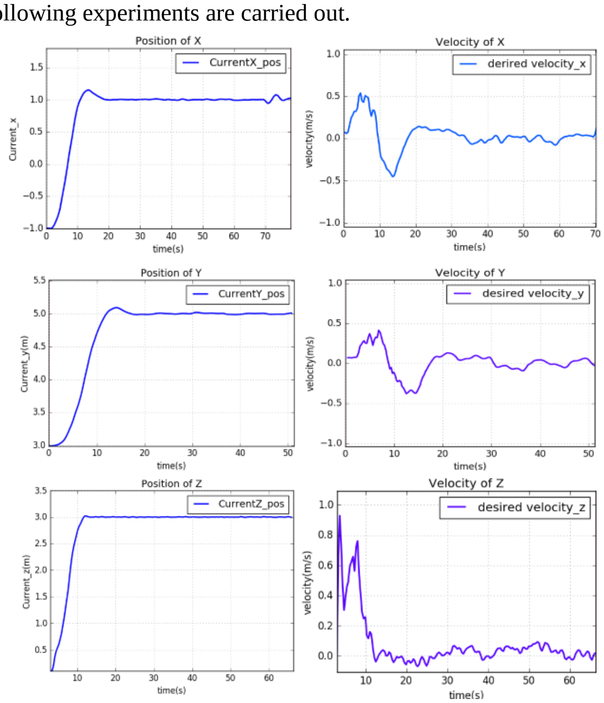

Figure 7: Controller performance test.

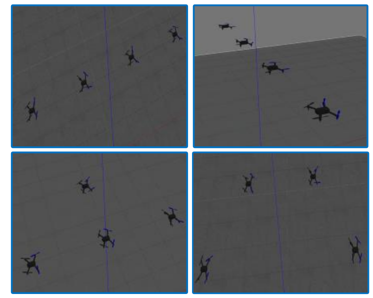

Figure 8: The four formations shown in Gazebo.

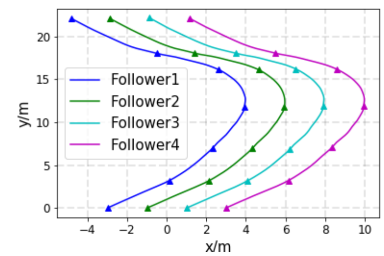

Figure 9: The trajectories of 4 quadrotors flying in the row formation on the XY plane.

First, taking UAV1 as an example to test the performance of formation keeping controller. Figure 7 shows the position changes of UAV1 in X-Y-Z three-direction channels and the corresponding speed commands obtained by the formation maintenance controller. This indicates that each quadrotor can gradually stabilize at its desired position with small overshoot.

Then, the formation keeping method is verified according to four specific formations pre-designed. Figure 8 is the four formations shown in Gazebo, which are row formation, column formation, triangle formation and wedge formation, respectively. Figure 9 shows the trajectories of 4 quadrotors flying in the row formation on the XY plane. As can be seen from the two figures, the four quadrotors can maintain the preset formations.

4.2 Simulation Experiment for Formation Transformation

The simulation experiments for formation transformation mainly verifies the feasibility of the collision avoidance strategy using the virtual repulsion force. Here the location of the virtual leader is fixed at (0,0), and the flight heights of all the quadrotors are set as the same, only considering the situation on the XY plane.

Before introducing the virtual repulsive force, we conduct several formation transformation experiments. Due to the specificity of the formation design, in these experiments there are cases where no collision occurs during the formation transformation, and also cases where the collision occurs. As shown in Figure 10, the triangular formation is transformed into a wedge formation, during which there is no collision between each quadrotor. Figure 11 shows the process of the primitive wedge formation changed into the column formation. It can be seen from the figure that the two four-rotor UAVs are too close at the same time, which causes a collision.

Then, we take several formation transformation experiments after the virtual repulsive force is introduced. In order to make a comparison with the experiments without repulsion constraint, the quadrotor formation is transformed from a wedge formation into a column formation after the repulsion constraint is added, which is shown in Figure 12. It indicates that there is no collision among all the quadrotors, which verifies the feasibility of the collision avoidance strategy.

Remarks: In Figures 10, 11, and 12, 'start' represents the starting position, 'end' represents the target position, and each 'process' represents the position of each UAV in the formation during formation transformation.

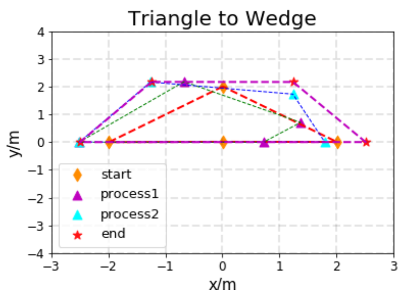

Figure 10: Triangle-to-wedge transformation without repulsion constraint (no collision).

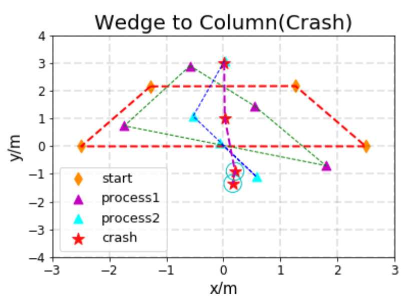

Figure 11: Wedge-to-column transformation without repulsion constraint (crash).

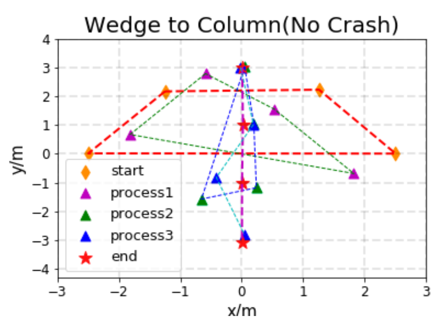

Figure 12: Wedge-to-column transformation with repulsion constraint (no crash).

5 CONCLUSION

This paper takes multiple quadrotor UAVs as the research object, and mainly solves the problem of formation keeping and transformation. Firstly, for the formation keeping control problem, a first-order controller using ADRC method is constructed based on virtual leader-follower structure to achieve the predetermined formation. Then, the formation changing strategy is designed by introducing a virtual repulsion force to avoid possible collision among the UAVs. The proposed method is verified to be effective by the multi-UAV collaborative simulation platform. However, the designed control method regards the quadrotor UAV as a first-order particle model and assumes its orientation angle $\psi_i \rightarrow 0$, which simplifies the analysis process and also reduces the application range of the method. In future work, we will focus on the research of formation transformation and obstacle avoidance behavior in more complex scenarios and environment.

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