Formation control of UAVs based on artificial potential field

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Abstract. The problem of UAVs' formation control in the process of motion is investigated in this paper. A formation control method based on artificial potential field of UAVs is proposed, established on the collision avoidance, aggregation and speed matching rules of UAVs. First establish the UAVs' kinetic model in accordance to the motion rules, then design the formation control algorithm based on artificial potential field function, which is used to control the formation during the movement of UAVs. Finally, the results of simulation experiment show that the proposed formation control method in this paper is effective and has the advantages of easy realization, good real-time performance and excellent robustness.

1 Introduction

Compared with a signal unmanned aerial vehicle (UAV), the UAV swarms(UAVs) coordinated formation has a great number of advantages. For example, UAVs coordinated formation can improve the efficiency of detection tasks, reduce flight energy consumption, enhance the ability of handing unexpected events and so on. It is obvious that the UAVs coordinated formation flight is an important development trend of UAV, which has a promising prospect. However, it is difficult to realize the complete autonomous decision-making function of UAVs formation flight, and we can hardly achieve a high degree of large-scale intelligent cooperative formation flying of UAVs. Therefore, it is of great significance to carry out the research of data fusion technology, sensing technology, task allocation technology, path planning technology, formation control technology, communication network technology and virtual/physical verification platform technology[1-3], etc. This paper mainly discussed the formation control problem of UAVs.

There are an abundant of research achievements of the UAVs formation control problem. In [4], Wang Xiaofan studied the multi-agent swarms with a virtual leader, realized that the multi-agent swarms could track the virtual leader's motion in a default formation, at a uniform speed. In [5], Peng Jianliang proposed a flexible formation control algorithm of multi-agent swarms based on the combination of artificial potential field gradient and virtual leaders, which can realize flexible formation of multi-agent swarms without velocity matching. In [6], Liang Xiaolong investigated the problem of autonomous escorting fleet of UAVs based on artificial potential field theory, proposed a swarm transport path planning method and a swarm behavior control method, which realized the

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path planning in the planning space, and achieved the swarms' evasion to the fixed threat. In [7], Liu Huan proposed a state estimation algorithm and a distributed leader-follower formation control method based on back-stepping, accomplished the simulation experiment of the formation flight of multiple UAVs. In 2014, Keio University, Kuriki invested the cooperative formation control problem of UAVs, a cooperative formation control strategy with anti-collision ability was proposed, which realized the cooperative formation flight and collision avoidance of the quadrotor UAVs^[8]. In 2015, A distributed formation controller based on the behavior rules was proposed by Shin, the controller is designed by the adjacent UAVs' status information, which can improve the robustness of UAVs formation^[9].

According to the problem of UAVs' formation control, a formation control method based on artificial potential field of UAVs is proposed, established on the collision avoidance, aggregation and speed matching rules of UAVs, and simulation experiment results show that the method is easy to be realized and suitable for the formation control of UAV swarms.

2 Kinetic Model of UAVs

The kinetic model of UAVs is established on rules, which mainly include aggregation/disaggregation rules, formation transformation rule and so on. These rules constitute the rule library of UAVs' motion. To avoid the distraction or collision of UAVs, three basic principles should be obeyed for each UAV, that is collision avoidance, speed matching and aggregation, which is described by the R-A model in Figure 1.

Establish three concentric circles with UAV i as the center of the circles, the outermost circle of Figure 1 is the perception range of UAV i , the inner region near to UAV i is called repulsive region, which will provide repulsive force to the UAV i , and UAV i should try to adjust the distance from other UAVs in this region to avoid collision, this region is expressed as $R_r^i = \{x_i | 0 < d_{ij} \leq d_r, x_i \in R_n\}$. The outermost grey region far from UAV i is called attractive region, other UAVs in this region will provide attractive force to the UAV i , and UAV i should try to pull closer the distance from other UAVs in this region to avoid dispersion, this region is expressed as $R_a^i = \{x_i | d_m < d_{ij} \leq d_a, x_i \in R_n\}$. The middle blue region between repulsive region and attractive region is called unanimous region, which mean that the distance between UAV i and other UAVs in this region is suitable, the repulsive force and attractive force between them is balanced, this region is expressed as $R_m^i = \{x_i | d_r < d_{ij} \leq d_m, x_i \in R_n\}$. And x_i represent the position of UAV i , d_r represent the radius of repulsive region, d_m represent the boundary distance of unanimous region, d_a represent the boundary distance of attractive region, d_{ij} represent the distance between UAV i and UAV j .

Fig. 1. R-A model.

Consider that a UAV swarm consists of M UAVs, and $X=(x_1, x_2, \dots, x_i, \dots, x_M)$ represent the set of position vectors of UAV swarms, $V=(v_1, v_2, \dots, v_i, \dots, v_M)$ represent the set of velocity vectors of UAV swarms. Knowing that $x_i \in \mathbb{R}^n$ is the position vector of UAV i , and $v_i \in \mathbb{R}^n$ is the velocity vector, establish the motion equation of UAV i as follow:

$$\dot{x}_i = v_i \quad (1)$$

From the R-A model, we know that the velocity of UAVs will be influenced by three kinds of virtual forces, assume that v_i^r 、 v_i^m 、 v_i^a are the speed component of v_i , produced in the repulsive region, unanimous region and attractive region respectively, which can be expressed as follows:

$$\begin{cases} v_i^r = \sum_{j \in R_r} k_{ij} \left(\frac{d_r + k_{ij}}{d_{ij} + k_{ij}} - 1 \right)^2 & 0 < d_{ij} < d_r \\ v_i^m = \sum_{j \in R_m} v_j & d_r < d_{ij} < d_m \\ v_i^a = \sum_{j \in R_a} d_{ij} \left(\frac{1}{d_a - d_{ij}} - \frac{1}{d_a - d_m} \right) & d_m < d_{ij} < d_a \end{cases} \quad (2)$$

In (2), k_{ij} represent the control coefficient of repulsive force between UAV i and UAV j , which is much smaller than the d_r .

3 Formation Control Algorithm of UAVs

It can be inferred from (1) that, in order to control the UAVs' position to form the expected formation, we should first design the function configuration of v_i .

Set a virtual leader in the swarms, then there would exist two kinds of forces acting on the UAV i , one is from the virtual leader, the other one is from the other UAVs in the UAV swarms, and the strength and direction of force is determined by the distance between UAV i and other UAVs or the virtual leader. According to the aggregation and collision avoidance rules of the UAV swarms, establish the motion equation of UAV i as follow:

$$\dot{x}_i = g^i(x^i - x^L) + \sum_{j=1, j \neq i}^M g^{ij}(x^i - x^j), \quad i=1, \dots, M \quad (3)$$

In (3), $x^i \in \mathbb{R}^n$, $x^j \in \mathbb{R}^n$, $x^L \in \mathbb{R}^n$ represent the position vector of UAV i , UAV j and the virtual leader respectively. And $g^i(\cdot)$ represent the relation function between UAV i and virtual leader, $g^{ij}(\cdot)$ represent the relation function between UAV i and UAV j .

The functions $g^i(\cdot)$ and $g^{ij}(\cdot)$ are constructed based on the three basic principles of UAVs (collision avoidance, speed matching and aggregation), which is expressed as follow:

$$g^i(x^i - x^L) = -a_i \frac{x^i - x^L}{\|x^i - x^L\|} \left[1 - \frac{\delta_i}{\|x^i - x^L\|} \right] \quad (4)$$

$$g^{ij}(x^i - x^j) = -a_{ij} \frac{x^i - x^j}{\|x^i - x^j\|} \left[1 - \frac{\delta_{ij}}{\|x^i - x^j\|} \right] \quad (5)$$

In (4) and (5), $a_i \in \mathbb{R}^+$ represent the velocity parameter, which determines the modulus of the virtual force produced by the artificial potential field. And $\delta_i \in \mathbb{R}^+$ is called equilibrium distance, which mean that when the distance between UAV i and virtual leader is equal to δ_i , then the repulsive force and attractive force between the virtual leader and the UAV i are equal.

Under the control of the artificial potential field, when the UAV swarms are in motion, two kinds of forces will have an effect on the swarms. One is the attractive/repulsive forces between UAV i and other UAVs, which mainly decide the formation style of swarms; the other one is the attractive/repulsive force from the virtual leader, which provide a constraint on the formation style and play a role in guiding the flight direction of UAVs, and the UAV swarms will form a specific formation according to the value of a , δ_i and δ_{ij} , which is shown in Figure 2, 4 UAVs are represented by 4 striped rectangular squares, the virtual leader is represented by a red circle, it can be seen from the Figure 2 that when the value of δ_i and δ_{ij} (i=1,2,3,4; j=1,2,3,4) is determined, then the formation of 4 UAVs is confirmed.

Fig. 2. Illustrative diagram of UAVs' formation.

4 Simulation Results

To verify the feasibility and correctness of the algorithm, the UAVs' formation control algorithm is simulated and analysed. The objective of the experiment is to realize that, when the task command is reached, UAVs can form the default formation quickly under the control of artificial potential field, then following the virtual leader, move as a swarm in the direction of destination with stable formation, reach the target position with default formation finally.

In the simulation experiment, the UAV swarms consist of 6 UAVs and one virtual leader, the default formation of UAVs is shown in Figure 3, the red circle represent the virtual leader, six green blocks represent six UAVs, and they have formed an equilateral triangle formation.

Fig. 3. UAVs default formation.

Firstly, the velocity parameter a in formula (4) and (5) is set as 5, the location of the selected virtual leader is set as (35, 35,30), as well as the destination. Running the simulation program, the distribution of 6 UAVs in three-dimensional space is shown in Figure 4. It can be seen from Figure 4 to Figure 7 that six UAVs are in a random position at $t = 0$, when $t=1.6s$, the UAVs have clustered into swarms and move toward the virtual leader, form the default formation at $t=3.8s$, finally, the six UAVs have form the default formation with the virtual leader. It can be seen from the simulation results that six UAVs started to gather when the simulation started and would quickly assembled from a dispersed state into the default formation. When moving toward the destination, the formation of UAVs can always be maintained. Finally, the UAVs could reach the target position with default formation, which is shown in Figure 7. The simulation results show that the objective of the simulation experiment have been achieved.

Fig. 4. Location of 6 UAVs at $t=0s$

Fig. 5. Location of 6 UAVs at $t=1.6s$

Fig. 6. Location of 6 UAVs at $t=3.8s$

Fig. 7. Location of 6 UAVs at $t=6.5s$

Fig. 8. UAVs track in three-dimensional space

Fig. 9. UAVs track in x-y plane.

The track of UAVs formation flight in three-dimensional space and x-y plane are shown in Figure 8 and Figure 9 respectively, the red circle represents the virtual leader, and six paths with different color represent the flight path of six UAVs. It can be seen from the Figure 8 and Figure 9 that the motion of UAVs is irregular at the beginning, when they cluster into a swarm, they would flight toward the virtual leader neatly, in a consistent direction. The track diagrams of UAVs illustrate that under the control of proposed formation control algorithm, UAVs would form a swarm quickly, and maintain the default formation stably during the motion, reached the destination with default formation finally. The simulation results show that the proposed formation control method is effective, and the objective of experiment has been realized.

5 Conclusion

According to the problem of UAVs' formation control in motion, a formation control method of UAVs based on artificial potential field is proposed, established on the collision avoidance, aggregation and speed matching rules. In the simulation experiment, UAV swarms could quickly assemble from a dispersed state into the default formation under the control of proposed method, and move toward the destination with a stable formation, reach the target position with default formation finally. The simulation results show that the proposed formation control method in this paper is effective and has the advantages of easy realization, good real-time performance and excellent control effect. Future work should focus on the motion control of UAVs in complicated environment with multiple obstacles, as well as formation transformation problems during the UAVs movement.

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