A UAV Cooperative Formation Capability Evaluation Method

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***Abstract*—Aiming at the problem that there is no unified and comprehensive formation capability evaluation method in the field of UAV cooperative formation. A UAV cooperative formation capability evaluation method based on the $l-l$ description method of UAV formation is proposed. This method proposes the $l-l-l$ three-dimensional UAV formation description method, expands the $l-l$ UAV formation description method to three-dimensional space. This evaluation method converts the position information of the UAV swarms from the world coordinate system to the formation coordinate system, so that the evaluation process can get rid of the geographic space. At the same time, only the position information of the UAV swarm is required to comprehensively evaluate the cooperative formation capability of the UAV swarm, evaluation indicators include formation time, formation hold, formation support, formation error, formation density, formation time mutual interference probability density, formation space mutual interference density, etc.**

Keywords- UAV formation; evaluation framework; UAV simulation.

I. INTRODUCTION

Multi-UAV swarm cooperative formation means that UAVs have computing and decision-making capabilities, can independently undertake part of the system tasks. The UAVs coordinate with each other, perceive and interact with the surrounding information, and gradually optimize during the movement process, so that the results tend to be consistent until the entire formation control task is completed. Multi-UAV cooperative formation is a manifestation of self-organizing system, which can be simply described as N UAVs distributed in various locations. UAVs can only perceive UAVs within their own communication range and cannot acquire other UAVs. The position information of N UAVs, through the information interaction with neighbors, moves to the target position in the formation, until all UAVs reach the target position to form the target formation. UAV formation, as the basis for UAV swarm movement and mission execution, plays an important role in UAV swarm coordinated flight, decision execution, and mission planning. At present, there are many researches on the single key technology of UAV swarms, but there is still a lack of research on the evaluation of the collaborative formation capability of UAV swarms.

Among the existing main methods, reference [1] uses the formation connection safety distance margin to evaluate the cooperative formation capability of UAV swarms and uses the distance from obstacles to evaluate obstacle avoidance ability. This method can effectively evaluate the reliability and density of the formation, but it cannot evaluate the shape of the formation. Evaluation; Reference [2] uses the formation error as the formation capability evaluation index, which calculates the position error between the actual formation of the UAV swarm and the corresponding UAV in the expected formation. This method can evaluate the shape of the formation, but when the UAVs in the formation exchange positions, although the formation does not change, the indicator will still return the wrong result of the formation; Reference[3] add parameters such as UAV speed, heading, and flight altitude on the basis of [2]. At the same time, the evaluation of UAV formation hold capability is introduced, but the fundamental problem is still not solved; Reference [4] and Reference [5] evaluated the UAV swarm formation by the UAV heading, speed, altitude process data curve and flight trajectory during the UAV formation process. This evaluation method does not have a numerical representation through human observation, so it is difficult to compare and evaluate intuitively; Reference [6] uses relative distance error and formation tracking error evaluated the UAV swarm formation. This method lacks the evaluation of formation density and collision-related indicators

In view of the current needs of most UAV swarms for collaborative formation capability evaluation, combined with the existing evaluation methods, this paper proposes a UAV collaborative formation capability evaluation method based on the $l-l$ UAV formation description method. This evaluation method converts the position information of the UAV swarms from the world coordinate system to the formation coordinate system, so that the evaluation process can get rid of the geographic space. At the same time, only the position information of the UAV swarm is required to comprehensively evaluate the cooperative formation capability of the UAV swarm, evaluation indicators include formation time, formation hold, formation support, formation error, formation density, formation time mutual interference probability density, formation space mutual interference density, etc. Due to the use of the relative coordinates of the formation, the evaluation method can perform continuous real-time evaluation for the entire formation flight process. In this paper, a formation flight system consisting of five quadrotor UAVs is simulated, and the evaluation method proposed in this paper is used to evaluate this formation flight system capability. The evaluation results demonstrate the effectiveness of the evaluation method.

2767-6684/22/$31.00 ©2022 IEEE
DOI 10.1109/DSA56465.2022.00091

II. A FRAMEWORK FOR EVALUATING UAV COOPERATIVE FORMATION CAPABILITY

The evaluation method of UAV cooperative formation capability proposed in this paper is based on the $l-l$ UAV formation description method. In terms of UAV formation research, Desai et al. [8] of Drexel University in the United States proposed two types of feedback controllers to maintain the formation of mobile robot teams. The two controllers correspond to the two-dimensional plane description methods of the two types of formations. One is the $l-\psi$ method, which uses the relative distance and included angle between each UAV in the formation and the formation reference point to describe the formation. The other is the $l-l$ method, which uses the distance between the position of each UAV and the reference point of the formation on the coordinate axis to describe the shape of the formation.

Figure 1. shows the use of $l-\psi$ method (left) and $l-l$ method (right) to describe the rhombus formation, U1 UAV is selected as the formation reference point, ψ_F is the movement direction of the U1 UAV, ψ_{U2}, ψ_{U3} is the angle between the U2, U3 and U1 moving directions, L_{U2}, L_{U3}, L_{U4} is the Euclidean distance between U2, U3, U4 and U1; $L_{U*}x$, $L_{U*}y$ is the relative coordinate of U* UAV in the coordinate system with U1 UAV as the origin.

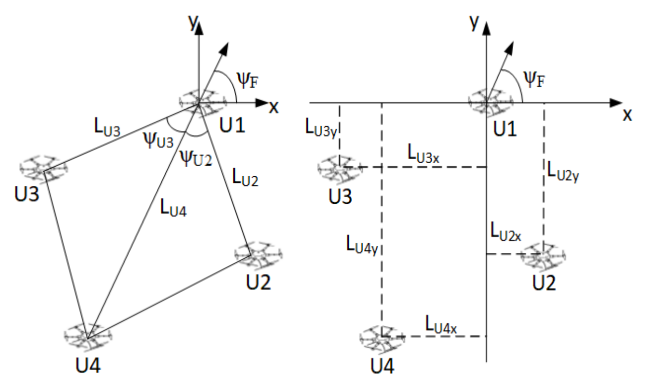

Figure 1. Diamond formation $l-\psi$ method (left), $l-l$ method (right) description.

Since the actual UAV swarm is a cooperative formation in the three-dimensional world, this paper extends the $l-l$ UAV formation description method to the three-dimensional space, Propose the $l-l-l$ method to describe the 3D formation. At the same time, this method selects the centroid of the formation as the reference point of formation coordinates in order to prevent the problem that the evaluation cannot be performed due to the failure of formation node when the node is selected as the reference point. This method can dynamically adjust the target formation description information according to the change of the number of UAVs in the UAV formation, and effectively prevent the evaluation failure caused by the damage and disconnection of the UAVs. The positive direction of the coordinate system is consistent with the UAV formation heading coordinate system, and the world coordinates of the UAV's center of mass are used as the actual coordinates of the UAV. According to the actual coordinates of each UAV in the formation, the centroid of the UAV formation and the formation coordinates of each UAV in the formation can be calculated. This relationship can be expressed in the form of a matrix, assuming that there are N UAVs in the UAV formation, using F_{xyz} represents the world coordinate position of the UAV, C_{xyz} represents the centroid of the UAV formation:

$$F_{xyz}=\begin{bmatrix} x_1, y_1, z_1 \\ x_2, y_2, z_2 \\ \vdots \\ x_N, y_N, z_N \end{bmatrix} \tag{1}$$

$$C_{xyz}=\begin{bmatrix} \frac{x_1+x_2+\cdots+x_N}{N}, \frac{y_1+y_2+\cdots+y_N}{N}, \\ \frac{z_1+z_2+\cdots+z_N}{N} \end{bmatrix} \tag{2}$$

The description of the method to convert the UAV formation F_{xyz} to $l-l-l$ is as follows (3) :

$$F_{xyz}^{l-l-l}=\begin{bmatrix} x_1-C_x, y_1-C_y, z_1-C_z \\ x_2-C_x, y_2-C_y, z_2-C_z \\ \vdots \\ x_N-C_x, y_N-C_y, z_N-C_z \end{bmatrix} \tag{3}$$

Among them, F_{xyz}^{l-l-l} represents the coordinate matrix of N UAVs in the formation coordinate system.

According to the $l-l-l$ method for describing the shape of 3D UAV formations. This paper proposes an evaluation method for UAV cooperative formation capability. In this evaluation method, the expected UAV formation needs to be described by the $l-l-l$ method, and the actual coordinates of the UAV formation are replaced by the $l-l-l$ method description format according to the (3) method,. This operation frees the UAV formation from the actual geographic space constraints, so that the evaluation method can conduct continuous real-time evaluation of the entire formation flight process. At the same time abstract the expected formation without determining the specific formation coordinates. This evaluation method evaluates the collaborative formation capability of UAV swarms from the aspects of formation time, formation maintenance, formation support, formation error, formation density, formation time mutual interference probability density, formation space mutual interference density, etc. The evaluation framework is shown in Figure 2.

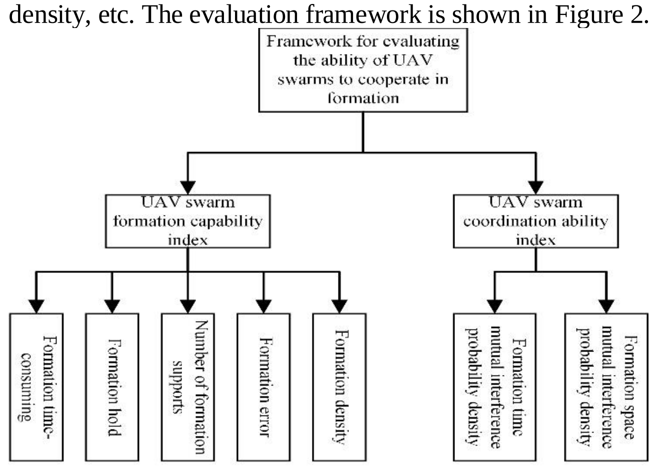

Figure 2. UAV swarm collaborative formation c apability framework.

The UAV swarm collaborative formation capability framework includes two parts: the UAV swarm formation capability index and the UAV swarm collaboration capability index, which evaluate the UAV swarm formation capability and coordination capability respectively. The UAV swarm formation capability index includes the formation time-consuming, formation hold, formation support number, formation error, formation density, the UAV swarm coordination capability index includes formation time mutual interference probability density, formation space mutual interference probability density.

The formation time-consuming index is defined as the time it takes for the UAV swarm to form a stable formation from take-off:

The formation hold index is defined as the time expectation for the UAV swarm to maintain a stable formation;

The indicator of formation support quantity is defined as the total number of shapes that can be changed by the UAV swarm;

The formation error index is defined as the average coordinate error between the actual formation coordinates and the expected formation coordinates of the UAV swarm under the description of the $l-l-l$ method;

The formation density index is defined as the number of UAVs in a unit area of a UAV swarm;

The formation time mutual interference probability density index is defined as the average probability of collision between UAVs in unit time;

The probability density index of mutual interference in formation space is defined as the average probability of collision between UAVs within a unit airspace.

III. Evaluation index system of UAV swarm collaborative formation capability

According to the UAV swarm collaborative formation capability evaluation framework, the formation capability and coordination capability evaluation indicators will be calculated based on the $l-l-l$ formation description method.

A. UAV swarm formation capability index

1) *Formation time-consuming*

This indicator evaluates the time from the take-off of the UAV swarm to the formation of a stable formation. It is stipulated that the distance between the coordinates of the UAVs and the coordinates of the expected formation is less than 2 meters, and the formation is maintained for more than 3 seconds, it is considered that a stable formation is formed. The specific calculation process is shown in Figure 3.

First, the x, y, and z coordinates of the UAVs in the actual formation and the expected formation are weighted and added, and then sorted in ascending order to determine the corresponding position information of each UAV in the expected formation. The coordinate weight can be set according to the UAV formation shape and the use of the coordinate system. The weight of the coordinate axis that has a great influence on the formation shape can be appropriately increased, so that the position characteristics between UAVs are more obvious. For example, in a triangular formation flying along the x-axis, the x-axis coordinates cannot effectively distinguish two planes flying side by side, while the y-axis coordinates have more obvious positional characteristics. The corresponding position information in the expected formation;

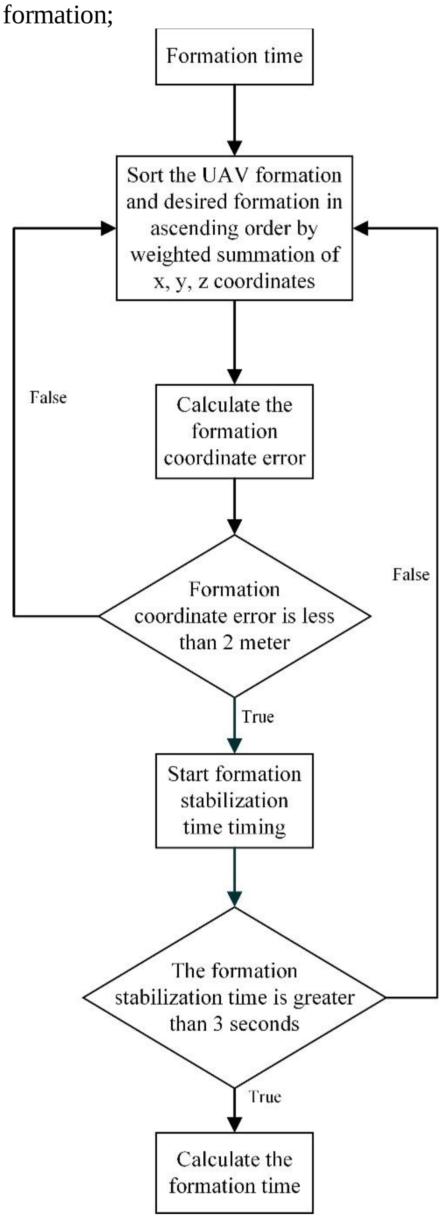

Figure 3. Formation time-consuming calculation process

Calculate the coordinate error between the actual formation coordinates of the UAVs in the formation and the expected formation coordinates, and use the Euclidean distance calculation;

If the coordinate errors of the UAVs are all less than 2 meters, the formation is considered to be formed, and the formation stabilization time is started. If the formation stabilization time is greater than 3 seconds, the formation is considered to have reached a stable state. The calculation formula of T_{FS} is as (4):

$$T_{FS} = T_S - T_I \tag{4}$$

Among them, T_S is the formation stabilization time, and T_I is the formation take-off time.

If a UAV with a coordinate error greater than 2 meter appears in the formation before the formation is stable, reset the formation stabilization time and repeat the above process.

If there is a faulty UAV during the execution of the UAV formation, which causes the slave formation to be lost, in order to prevent the faulty UAV from affecting the evaluation of the formation, when the UAV fails, the number of the faulty UAV can be sent to the evaluation process. , the evaluation process will delete the coordinates of the corresponding numbered UAVs in the expected formation, and recalculate the centroid of the new expected formation according to the remaining coordinates, re-transform the coordinates to generate a new desired formation, and continue to evaluate the remaining UAVs in the formation. to evaluate.

2) *Formation hold*

This indicator evaluates the time that the UAV swarm will maintain a stable formation after forming a stable formation. It is stipulated that the distance between the coordinates of each UAV formation in the UAV swarm and the desired formation coordinate is less than 2 meter2, and the formation is considered to be successful. Otherwise, the formation is ended. The formation stable state detection is the same as the formation time-consuming index, and the calculation formula is as (5):

$$T_{FK} = T_E - T_S \tag{5}$$

Among them, T_S is the formation stabilization time, and T_E is the formation holding end time.

3) *Number of formations supported*

This indicator evaluates the number of UAV formations that can be effectively supported by UAV swarms. According to the UAV swarms that can support each formation, a variety of expected formations are preset. For the calculation process, see Figure 4.

Check whether the UAV formation has reached a stable state;

Calculate the formation error between the actual formation and each expected formation. The formation error calculation method is the same as the formation time-consuming index;

Check whether there is a formation with a formation error of less than 2 meters. If there is, judge whether the formation has been supported. If not, add one to the number of formations supported.

4) *Formation error*

This indicator calculates and records the real-time average formation error of the UAV swarm during the operation. The calculation formula of the formation error E_F at each moment is as (6):

$$E_F = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(x_i^r - x_i^p\right)^2 + \left(y_i^r - y_i^p\right)^2 + \left(z_i^r - z_i^p\right)^2} \tag{6}$$

Among them, N is the number of UAVs in the UAV formation, x_i^r, y_i^r, z_i^r are the actual formation coordinates of the i-th UAV, x_i^p, y_i^p, z_i^p are the i-th UAV expected formation coordinates.

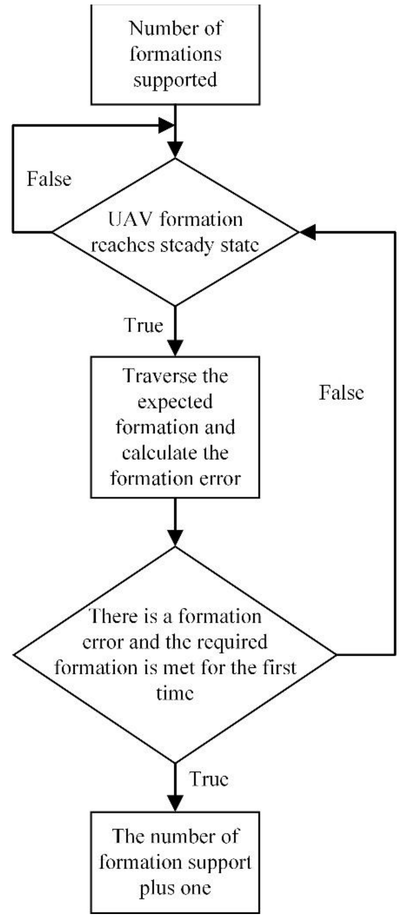

Figure 4. Number of formations supported

5) *Formation density*

This indicator calculates the number of UAVs in the unit airspace of the UAV swarms during operation, and the calculation formula is as follows:

$$D_F = \frac{N}{R_F} \tag{7}$$

Among them, N is the number of UAVs, and R_F is the projected area of the airspace occupied by the UAV formation.

R_F is calculated using the Graham scanning method, and the calculation process is as follows：

Select the UAV coordinate with the smallest y-axis coordinate in the formation as the reference UAV. If there are UAVs with the same y-axis coordinate, compare the x-axis and select the one with the smaller x-axis;

Calculate the polar angle of other UAVs to the reference UAV;

Sort UAVs in ascending order of polar angle (excluding datum points);

Starting from the reference UAV counterclockwise, calculate the rotation direction of the two vectors composed of the three adjacent UAVs with the middle UAV as the origin by the cross-multiplication method. If the cross-multiplication result is positive, the angle between the two vectors is less than or equal to 180 degrees, then the intermediate UAV may be the projected outer polygon vertex of the airspace occupied by the formation, which is added to the convex hull vertex stack to save, see Figure 5. ; Otherwise, the UAV is in the convex hull, delete the middle UAV from the stack and recursively move forward until the cross-multiplication result is not negative, add a new UAV node to continue the calculation, see Figure 6. .

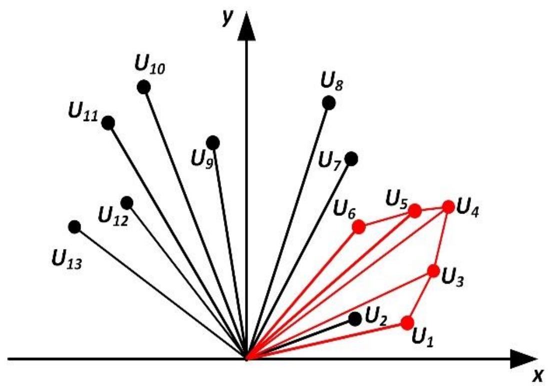

Figure 5. Cross-ride is the positive report to leave the UAV.

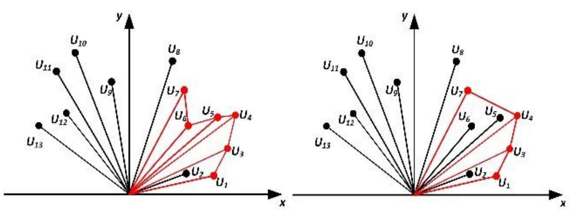

Figure 6. The cross product is negative, recursively delete points.

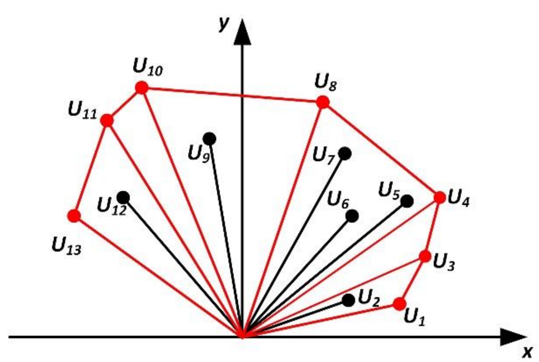

Figure 7. Graham scan method calculation results.

The area of the two-dimensional convex hull formed by the UAV formation R_F is calculated by the Shoelace formula to calculate. The formula is as (8):

$$R_F = \frac{1}{2}\left|\sum_{i=1}^{n} x_i(y_{i+1} - y_{i-1})\right| \tag{8}$$

Where n is the number of vertices of the UAV formation convex hull, x_i is the x-axis coordinate of the i-th UAV, y_{i+1}, y_{i-1} is the y-axis coordinate of the i+1th, i-1 UAV.

6) *Formation time mutual interference probability density*

This indicator is used to measure the ability of the UAV in the UAV formation to not interfere with each other (collision) within a specified time. The calculation formula is as (9):

$$P_F = \frac{\left(\sum_{t=1}^{T} \frac{C_t}{N}\right)}{T} \tag{9}$$

C_t is the number of collision individuals at time t, N is the number of UAVs in the UAV formation, and T represents the specified time period.

If the UAV is bound to the collision sensor, the sensor data will be directly read to count the number of collisions in the UAV formation; If not bound, use Euclidean distance between drones for evaluation. if the distance between the two UAVs is less than the UAV radius , it is considered that a collision occurs, and the calculation formula is as (11):

$$D_t = \begin{bmatrix} E_{00} & \cdots & E_{0N} \\ \vdots & \ddots & \vdots \\ E_{N0} & \cdots & E_{NN} \end{bmatrix} \tag{10}$$

$$C_t = NUM(D_t < R_{UAV}) \tag{11}$$

where D_t is the UAV formation spacing matrix at time t, E_{ij} is the Euclidean distance between the i-th UAV and the j-th UAV, and R_{UAV} is the UAV radius.

7) *Formation space mutual interference probability density*

This indicator is used to measure the ability of UAVs to not interfere with each other (collision) in the UAV formation flight airspace. The collision information acquisition method is the same as the formation time mutual interference probability density index. The formula is as (12):

$$P_F = \frac{\left(\sum_{t=1}^{T} \frac{C_t}{N}\right)}{S} \tag{12}$$

C_t is the number of collision individuals at time t, N is the number of UAVs in the UAV formation, and S is the projected area of the UAV formation flight airspace.

IV. Effectiveness Verification of the UAV Collaborative Formation Capability Evaluation Framework

The UAV swarm formation control model is simulated in the Unreal Engine 4 game engine [7], and the UAV collaborative formation capability evaluation framework proposed in this paper is used for real-time evaluation during the simulation process.

In the experiment, the number of UAVs is set to 5, and the initial settings of the UAV formation are shown in TABLE I.

TABLE I. UAV FORMATION INITIALIZATION SETTINGS

UAV	1	2	3	4	5
Location (m)	0,10,0	0,20,0	0,31,0	0,42,0	0,49,0
Speed (m/s)	(1,-1,1)	(0,1,1)	(-1,-1,-1)	(-1,0,1)	(-1,1,0)
Pitch (°)	0	0	0	0	0
Yaw (°)	45	30	50	-30	0
Roll (°)	0	1	2	-1	1

In this paper, the lead plane-wingman method formation model is used as the test object, and the UAV formation controller is realized by the LQR control method. The algorithm uses distributed control [9]. The wingman needs to obtain the information of the lead plane and make judgments to give control signals. Through the control of the relative positions of the lead plane and the wingman, the formation, maintenance and transformation. Through the formation controller, the wingman can quickly follow the speed of the long UAV, and the yaw angle changes and tends to be consistent, preventing formation confusion and collision between UAVs, so that the UAV formation can maintain the set formation well.

The simulation time is preset to 90s. The simulation process is shown in Figure 8. . The $l-l-l$ method is used to describe the formation. Described as (13):

$$F_0 = \begin{bmatrix} 6 & 0 & 0 \\ 1 & 5 & 0 \\ 1 & -5 & 0 \\ -4 & 10 & 0 \\ -4 & -10 & 0 \end{bmatrix} \tag{13}$$

After 45s, the remaining four UAVs are transformed into a rectangular formation and remain stable for 30s. The expected formation is described as (14):

$$F_1 = \begin{bmatrix} 5 & 5 & 0 \\ 5 & -5 & 0 \\ -5 & -5 & 0 \\ -5 & 5 & 0 \end{bmatrix} \tag{14}$$

The last four UAVs avoid obstacles and pass through the obstacle area, but not in formation.

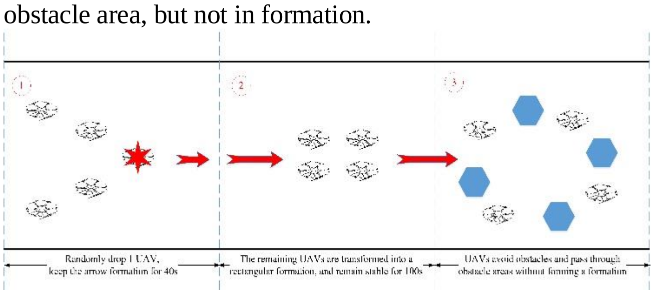

Figure 8. Simulation process

The formation movement track of the swarms is shown in Figure 9. . After the simulation starts, when the simulation time is 2.5s, the five UAVs fly from the initial position according to the planned path, and the formation has not yet been carried out at this time. The formation error shown in Figure 11. is 12m, and the initial position of the formation is relatively close, resulting in too high formation density. For the convenience of subsequent observation, the formation density shown in Figure 13. is set to 0 (UAVs /square meter), and the actual density is 23.7 (UAVs/square meter); Under the control of the formation algorithm, the formation error is rapidly reduced. When the simulation time is 17s, the formation error is reduced to less than 2m. When the simulation time is 20s, a stable arrow-shaped formation is formed. It can be calculated that the formation time of the UAV formation to form an arrow formation is 17.5s, and the formation density is also stabilized at 0.0014 (UAVs /square meter). At the same time, the number of supported formations is increased by one. See Figure 12. , Consistent with the actual flight path of the UAV formation shown in Figure 9. , because the initial position of the UAV formation is relatively close. Internal collision occurred in the initial stage of UAV formation to arrow formation. From Figure 13 and Figure 14, it can be seen that formation time mutual interference probability density within 5s reaches 0.9 (times/s), and formation space mutual interference probability density reaches 0.0325 (times/ square meter). With the end of the take-off process, the formation flight attitude tends to be stable, no more collisions occur;

At t=25s, one UAV (leading UAV) will be randomly forced to drop the line to simulate the failure of UAV. At this time, the remaining UAV formation fluctuates briefly, and the formation error increases to 8.3m. The formation algorithm adjusts the position of the UAV and restores the formation after 15 seconds. The formation hold time of the arrow formation is 15.5s in total. At this stage, the formation position deviation of U1 and U5 is the main source of formation error.

It can be seen from t=46s that the UAV formation began to switch to a rectangular formation. Due to the change of the target formation, the formation error rapidly increased to 3.9 meters; At t=50s, the formation error was reduced to within 2m. At t=53s the UAV formation forms a stable rectangular formation. It can be calculated that the formation time of the UAV formation to form rectangular formation takes 6s, and the number of formation supports is increased by one. Due to the rectangular formation, the formations are relatively close together, and the formation of UAVs converges, resulting in the formation density of intersecting arrow formations rising to 0.0018 (UAVs /square meter), and the formations of UAVs maintaining rectangular formations until t=70s. The total holding time is 17.5s. At this stage, the formation position offset of U1 and U4 is the main source of formation error.

When t=73s, the UAVs reach the obstacle area, and the UAVs form scattered formations to avoid obstacles. At this stage, the UAVs are not formed. However, because the expected formation is rectangular formation at this time, Figure 11. shows that the formation error is relatively large, so the formation capability is not evaluated at this stage. Only the formation coordination capability is evaluated. t = 90s, the drone formation passes through the obstacle area without collision, reach the end point, and end the simulation.

Figure 16. shows the calculation speed of each frame of images for seven indicators during the evaluation process. Using FPS (Frames Per Second) as the unit of measurement. It can be seen that the FPS of the evaluation module is stable at around 1000, the highest can reach 1350FPS, and the lowest can also maintain 650FPS. In actual use, affected by the communication performance of the UAV, the time-consuming of data acquisition will greatly increase and cannot reach the ideal state, but the experimental results are enough to prove that this evaluation method can meet the needs of real-time evaluation.

Figure 9. UAV formation simulation path

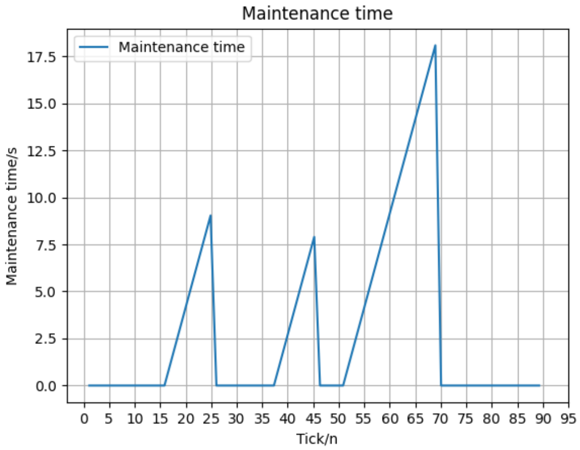

Figure 10. Formation hold

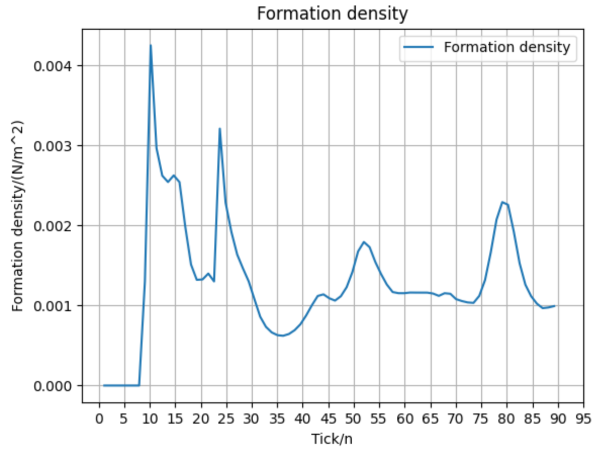

Figure 13. Formation density

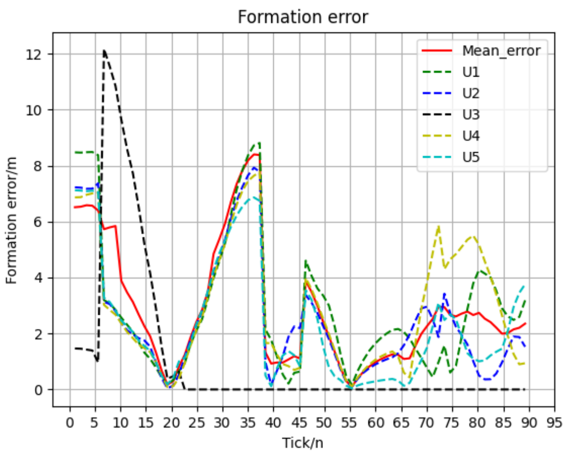

Figure 11. Formation error

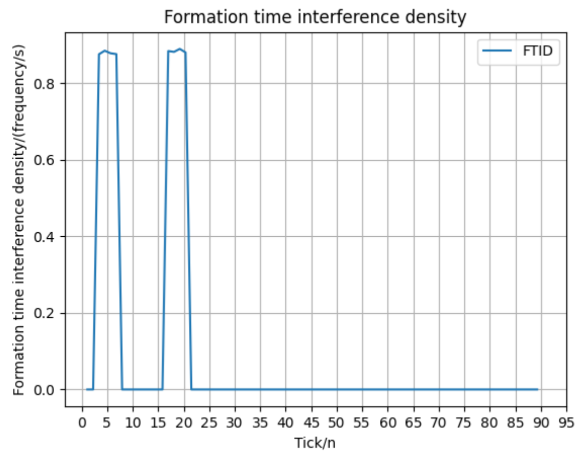

Figure 14. Formation time mutual interference probability density

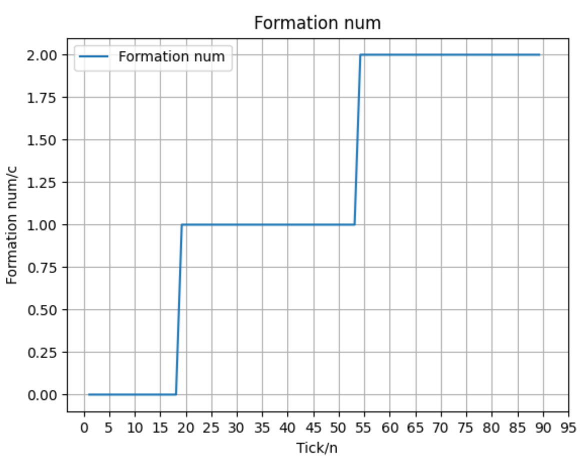

Figure 12. Number of formations supported

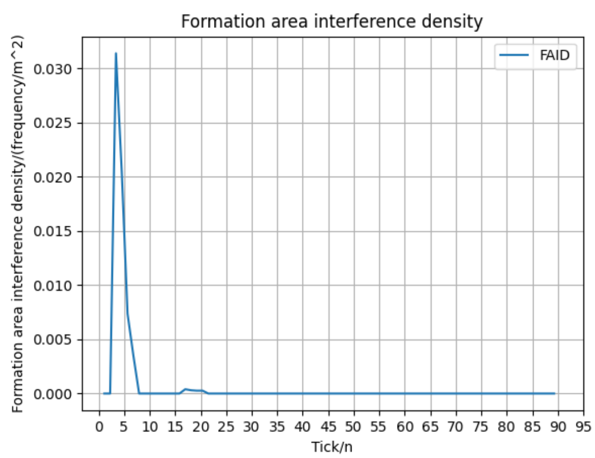

Figure 15. Formation space mutual interference probability density

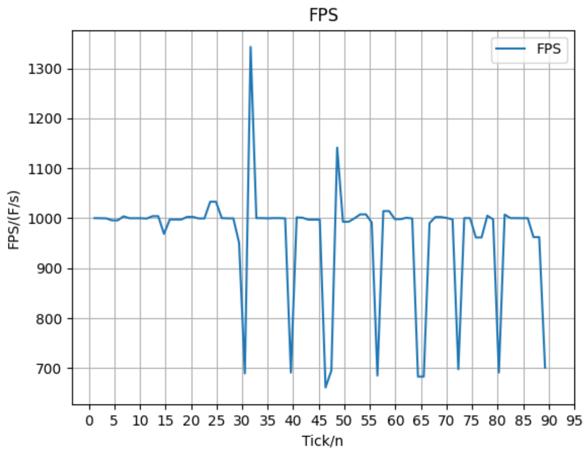

Figure 16. Evaluation Speed (FPS)

V. CONCLUSION

This paper proposes a method for evaluating the ability of UAV cooperative formation based on the $l-l$ UAV formation description method. This method builds a UAV swarm cooperative formation capability evaluation framework from two aspects: UAV swarm formation capability and UAV swarm coordination capability. The UAV swarm formation capability index includes formation time, formation hold, number of formations supported, and formation error, formation density. UAV swarm coordination capability index includes formation time mutual interference probability density, formation space mutual interference probability density.

First of all, the $l-l$ UAV formation description method applied to the two-dimensional scene is expanded, and the z-axis is added to expand it to the $l-l-l$ three-dimensional space UAV formation description method. At the same time, in order to prevent the problem that the evaluation cannot be carried out due to the failure of the UAV as the formation reference point. The formation coordinate reference point is selected as the centroid of the formation. This method can dynamically adjust the expected formation information according to the number of UAVs, and effectively prevent the evaluation failure caused by the damage and disconnection of UAVs. Secondly, this method converts the UAV swarm formation position information from the world coordinate system to the formation coordinate system of the $l-l-l$ formation description method. The evaluation method can get rid of the geographical space limitation and continuously evaluate the entire formation flight process in real time. At the same time, the expected formation can be abstracted, and there is no need to determine the specific formation coordinates.

In the index calculation, the method sorts the UAVs in the actual formation and the expected formation respectively according to the coordinate values of the formation. Automatically align the actual coordinates of the UAV with the desired coordinates for error calculation, without the need to manually bind the UAV location information to the UAV number. The Graham scanning method is introduced in the calculation of the formation density index, which effectively improves the calculation accuracy. The formation collision matrix is introduced to assist the calculation in the coordination ability evaluation indicators to simplify the calculation process.

The simulation test and flight verification show that the UAV cooperative formation capability evaluation method based on $l-l$ UAV formation description method has good applicability. The use of the formation coordinate system of the $l-l-l$ formation description method and the automatic error calculation method effectively simplify the parameters required for the evaluation of the UAV cooperative formation capability. The evaluation results are consistent with the UAV formation operation, which proves its effectiveness. At the same time, the evaluation speed of this evaluation method is stable at 1000FPS in the simulation environment, which is sufficient to meet the real-time evaluation needs.

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