Fixed-wing UAV Kinematics Model using Direction Restriction for Formation Cooperative Flight

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Abstract: Presently, existing fixed-wing UAV kinematics models typically require the planning algorithm to further smooth the results to meet the trajectory requirements of the starting direction, while the commonly used formation models often lead to track interference between formation members. In this paper, the formation cooperative flight of fixed-wing UAVs was modeled. First, the linear velocities in the three-dimensional direction of the traditional UAV model were changed to a linear velocity along the flight direction of the UAV, and the turning angular velocities and linear acceleration were set to establish the kinematics model. Then, based on the "Lead plane-Wingman" formation control structure, the order of friendly aircraft avoidance was defined by setting the priority of the formation members, and the target point of the wingman was dynamically calculated according to the target formation and real-time position of the leader plane. Finally, a UAV formation cooperative flight model was obtained. Considering the formation of five UAVs as an example, a simulation experiment was carried out, the results of which showed that the trajectory obtained based on the above model could meet the kinematics and collision avoidance requirements in formation flight of the fixed-wing UAVs.

1 INTRODUCTION

Presently, unmanned aerial vehicles (UAV) are widely used in many fields, such as disaster detection, low-altitude reconnaissance, atmospheric research, communication relay, disaster area search, and rescue missions (Qadir et al., 2021; Qu et al., 2014; Sivakumar & TYJ, 2021). Some of the tasks involved in these areas have security risks or require long periods of continuous operation, making them unsuitable for manned aircraft, contrast to UAVs (Rajasree & Jisha, 2015). Compared with the rotor UAV, the fixed-wing UAV has advantages of long flight distance, long flight time, high speed, and higher load capacity. It is suitable for missions with long continuous working hours and high requirements for airborne equipment (Y. et al., 2021). Currently, the mission execution capability of a single UAV is limited, and a UAV formation can improve the efficiency at which missions are executed. A reasonable formation can reduce task costs (i.e., by saving fuel) (Qiannan et al., 2014) and improve mission execution effectiveness (i.e., by increasing the search scope) (Seiler et al., 2002). The planning of a safe and feasible trajectory for each UAV according to preset formation requirements is an important task in the current fixed-wing UAV formation research (Gul et al., 2021; Sharma et al., 2021). Reasonable UAV kinematics and formation cooperative flight models can provide appropriate constraints and planning objectives for the trajectory planning of a UAV formation (Aggarwal & Kumar, 2020), which makes the planning results more feasible.

In the trajectory planning of UAVs, owing to certain limitations of fixed-wing aircraft, including flight direction and speed, there is a high demand for flight-path feasibility. The common method is to consider the UAV as a particle for trajectory planning purposes and then smooth the results to get a trajectory that meets the requirements (Huang et al., 2016; Maini & Sujit, 2016; Sahingoz, 2014). By using appropriate kinematic models to provide constraints, the algorithm can consider the requirements of the UAV in the track starting direction of the planning process. However, in the scenario of multiple UAVs flying together, coordination among the UAVs is the main problem. Changing the UAV formation requires changing the flight state of each UAV according to the

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mission requirements and environmental restrictions. In this regard, the cooperation of all UAVs required. That is, the flight trajectory of each UAV cannot be planned independently. If the planning is based on a simple formation model, interference of trajectories can easily occur, which may make members of the formation collide or result in difficulties maintaining the target formation. Therefore, the path planning algorithm must be based on reasonable UAV kinematics and formation models to ensure feasibility of the results (Tsourdos et al., 2011).

Based on the flight characteristics of fixed-wing aircraft, a kinematics model for the fixed-wing UAV can be established. According to the formation structure of "Lead plane-Wingman" (Zhu et al., 2017), the formation cooperation model of the UAV can be established by designing formation flight rules for both the lead plane and wingmen. Therefore, a fixed-wing UAV kinematics model and a UAV formation cooperative flight model are proposed in this paper. The main contributions of this study are as follows:

1. A kinematics model for the fixed-wing UAV is proposed. The linear and turning angular velocities along the flight direction of the UAV are used to replace the linear velocity in the three-dimensional direction of the traditional UAV model, and the linear acceleration is set, which meet the requirements of the starting direction of the UAV in the planning results.

2. A UAV formation cooperative flight model is proposed. Based on the formation structure of "Lead plane-Wingman", the target points of the wingmen are updated in real time according to the requirements of the formation and position of the lead plane in the process of formation flight. Priority is set for the members of the formation to specify the order in which UAVs avoid their teammates.

It should be noted that the situation addressed in this study is the path planning level of the UAV, which does not involve the design of the flight control system at the bottom of the UAV (Y. et al., 2021).

This paper is organized as follows: Section 2 introduces current related research. Sections 3 and 4 introduce the models proposed in this paper. Section 5 presents the verification and experimental analyses. Section 6 presents the conclusions and future work.

2 RELATED WORK

2.1 Kinematic Modeling of Fixed-wing UAV

Establishing a kinematics model for the UAV is the basis for trajectory planning. Feng et al. proposed a hybrid algorithm that can effectively deal with the influence of dynamic obstacles. However, due to the lack of kinematic models for fixed-wing UAVs, its planning result requires the UAV to avoid obstacles by hovering first and then making a detour, which is not a feasible flight trajectory (Feng et al., 2021). Chen et al. modelled a UAV and used the artificial potential field method to realize formation flight of multiple UAVs, but the model does not consider the flight characteristics of the fixed-wing UAV, which leads to a large oscillation in the flight path; therefore, this method is not ideal for the flight trajectory planning of the fixed-wing UAV (Chen et al., 2015). Phung and Ha combined many motion parameters of the UAV as constraints and used a planning algorithm to obtain the spherical vector-based particle swarm optimization algorithm, thereby optimizing the track point; however, this method does not consider the starting flight direction of the UAV (Phung & Ha, 2021). Manathara and Ghose established a fixed-wing UAV model to study the problem of multiple aircraft reaching a destination simultaneously and solved the constraint condition of the starting direction of the UAV using Dubins curve (Manathara & Ghose, 2012). However, the model only considers the direction constraint of two-dimensional space and requires UAVs to fly at a fixed speed; therefore, the planning result based on this model has difficulties meeting the requirements of UAVs in real scenarios.

2.2 Design of UAV Formation Cooperative Flight Model

Establishing a UAV formation cooperation model is important for UAV formation flight safety and formation adjustment flexibility. Zhang et al. modelled the formation of fixed-wing UAVs, but the proposed planning method had few constraints on the formation control model, resulting in poor coordination among teammates and lack of flexibility in formation adjustments (Zhang et al., 2018). Wei et al. proposed a path planning model for multiple UAVs based on the ant colony algorithm, but the model does not study the formation coordination strategy; therefore, the calculation results based on this model show that the trajectories among UAVs are independent and do not have the characteristics of formation flight (Bai et al., 2021). Zhu et al. established a multi-aircraft model for the formation maintenance of multiple UAVs, but the model only regulates the formation members in the formation maintenance stage and cannot provide constraints and planning objectives for the planning algorithm in the formation assembly stage (Zhu et al., 2017).

In summary, regarding meeting the motion performance constraints of the fixed-wing UAV, the existing research models have some problems, that is, the track is not smooth, the initial direction is not considered, and the speed of the UAV is strictly limited. In the research of formation flight, some of the formation models focus on maintaining the formation, while some prevent multi-aircraft trajectory conflict by avoiding path crossover. Therefore, these models have difficulties meeting the coordination and cooperation requirements of UAVs in formation flight.

3 KINEMATICS MODELING OF FIXED-WING UAV USING DIRECTION RESTRICTION

3.1 Position and Attitude Description of UAV

First, it is necessary to describe the position and attitude of the UAV. A coordinate system that is relatively stationary to the ground is defined, which is called an inertial coordinate system (ICS) in this study, and is marked as $S_f(o_f x_f y_f z_f)$. As shown in Figure 1, where o_f is a certain point on the ground, $o_f x_f$ points in a certain direction of the horizontal plane, $o_f x_f y_f$ is the horizontal plane, and $o_f z_f$ is perpendicular to the ground and points to the sky. This coordinate system conforms to the right-hand rule and is used to represent the position and attitude of the UAV in this study. This study focuses on the level of route planning; therefore, the state matrix, $\boldsymbol{P}$, of the UAV in the inertial system is defined as follows:

$$\boldsymbol{P} = [x\ y\ z\ \theta\ \psi]^T \tag{1}$$

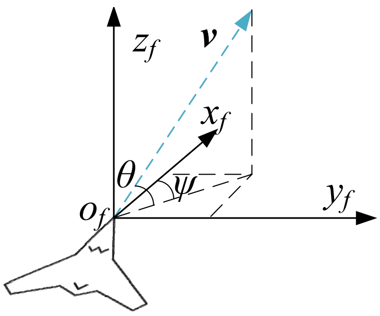

Figure 1: Inertial Coordinate System.

where x, y, and z are the coordinate positions of the UAV in the ICS and θ and ψ represent the attitude information of the UAV. θ is the pitch angle ($-\pi/2 \leq \theta \leq \pi/2$), and ψ is the yaw angle (azimuth) ($-\pi \leq \psi \leq \pi$). This study runs at the planning level and does not consider specific details of the UAV movement process; therefore, it is not necessary to define the roll angles of the UAV.

3.2 Motion State Modeling of UAV based on Direction Restriction

A coordinate system that is relatively stationary to the UAV is defined, which is called the vehicle coordinate system (VCS) in this study, and is denoted by $S_v(o_v x_v y_v z_v)$, where o_v is a fixed position on the UAV at some point in time, $o_v x_v$ points in the direction of the head of the UAV and is in the same direction during flight, $o_v y_v$ is parallel to the horizontal plane and points to the right side of the UAV, and $o_v z_v$ is vertically horizontal and points to the top of the UAV. This coordinate system conforms to the right-hand rule and is used to describe the motion state of the UAV. The motion state matrix of the UAV in the VCS is expressed as follows:

$$[v_l\ v_\theta\ v_\psi\ a_l\ a_\theta\ a_\psi]^T \tag{2}$$

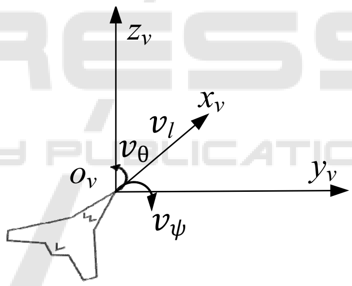

Figure 2: Vehicle Coordinate System.

As shown in Figure 2, the linear, pitching angular and yaw angular velocities of the UAV are denoted by v_l, v_θ and v_ψ, respectively. The linear, pitch angular and yaw angular accelerations of the UAV are denoted by a_l, a_θ and a_ψ, respectively.

The following assumptions are made about the kinematic characteristics of the fixed-wing UAV:

1.The linear acceleration of the UAV is constant, that is, a_l is constant.

2.The UAV turns at a constant angular velocity.

3.The velocities of the UAV have an upper limit, and the linear velocity has a lower limit, $v_{l_{min}}$, which is greater than 0.

The velocity matrix, $\boldsymbol{V}$, and the acceleration matrix, $\boldsymbol{a}$, are obtained as follows:

$$\begin{cases} \boldsymbol{V} = [v_l \; v_\theta \; v_\psi]^T \\ \boldsymbol{a} = [a_l \; a_\theta \; a_\psi]^T \end{cases} \quad (3)$$

According to the previous hypothesis, the relationship between the velocity and acceleration is as follows:

$$\boldsymbol{V}(t' + \Delta t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \boldsymbol{V}(t') + \boldsymbol{f}(t') \cdot \begin{bmatrix} \Delta t & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \boldsymbol{a} \quad (4)$$

$$\boldsymbol{f} = \begin{bmatrix} f_l & 0 & 0 \\ 0 & f_\theta & 0 \\ 0 & 0 & f_\psi \end{bmatrix} \quad (5)$$

where $\boldsymbol{V}(t')$ is the velocity matrix of the UAV at time t', $\Delta t(s)$ is the step size of the time advance, and $\boldsymbol{f}$ is the velocity change trend matrix of the UAV. The values of f_l, f_θ, and f_ψ are selected from 1, 0, and -1, respectively, according to the requirements of the planning algorithm at time t'. Consequently, the relationship between the position and attitude of the UAV as well as its velocity are obtained as follows:

$$\begin{cases} \dot{x} = v_l \cos\theta \cos\psi \\ \dot{y} = v_l \cos\theta \sin\psi \\ \dot{z} = v_l \sin\theta \\ \dot{\theta} = v_\theta \\ \dot{\psi} = v_\psi \end{cases} \quad (6)$$

4 PRIORITY AVOIDACE BASED UAV FORMATION COOPERATIVE FLIGHT MODEL

4.1 Description of Formation Location

The formation in this study consists of a lead plane and several wingmen. The role of the lead plane in the formation is to lead the formation to fly to the target area; therefore, the target point of the lead plane is set in advance. The positions of the wingmen in the target formation become their local target point, which changes with the state of the lead aircraft. Therefore, the target point of a wingman at a certain time must be determined by the preset formation parameters and current position and posture of the lead plane.

As shown in Figure 3, considering the V-shaped formation as an example, the coordinate system represented by the black solid line is the ICS. The blue solid line represents a UAV as the lead plane, and the blue dotted lines represents the local target points of the wingmen. At this time, the lead plane is located at a certain point in the ICS. The coordinate system, represented by the blue dotted line, represents the VCS of the lead plane. If the lead plane is UAV 0, then the equation for calculating the local target points of the wingmen at a certain time is as follows:

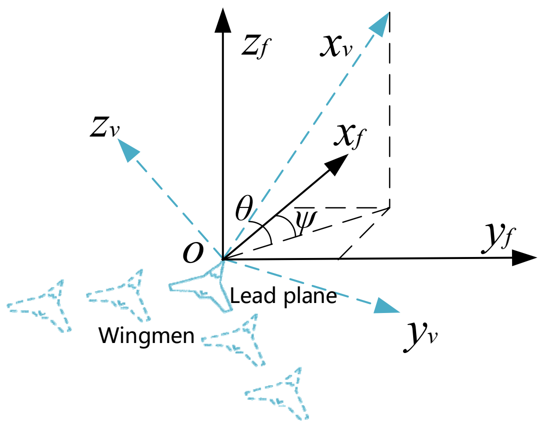

Figure 3: Method for Determining Wingmen Target Point.

$$\boldsymbol{G}_j = \boldsymbol{A}_{vf} \cdot \boldsymbol{B}_{vf} \cdot \left[x_j^{gv} \; y_j^{gv} \; z_j^{gv}\right]^T + [x_0 \; y_0 \; z_0]^T \quad (7)$$

$$\boldsymbol{A}_{vf} = \begin{bmatrix} \cos\psi_0 & -\sin\psi_0 & 0 \\ \sin\psi_0 & \cos\psi_0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$$\boldsymbol{B}_{vf} = \begin{bmatrix} \cos\theta_0 & 0 & \sin\theta_0 \\ 0 & 1 & 0 \\ \sin\theta_0 & 0 & \cos\theta_0 \end{bmatrix} \quad (9)$$

where matrix $\boldsymbol{G}_j = \left[x_j^g \; y_j^g \; z_j^g\right]^T$ is the local target point of *j*th wingman (*j* = 1, 2,…, *n*) in the ICS, $\boldsymbol{A}_{vf}$ and $\boldsymbol{B}_{vf}$ are matrices that transform coordinates from the VCS to the ICS, ψ_0 and θ_0 are the yaw and pitch angles of the lead plane in the ICS, respectively, $\left[x_j^{gv} \; y_j^{gv} \; z_j^{gv}\right]^T$ is the target point of a wingman under the VCS of the lead plane, $[x_0 \; y_0 \; z_0]^T$ is the position of the lead plane under the ICS.

4.2 Coordination Rules for Formation Members based on Avoidance Priority

There may be a risk of collision between UAVs during flight; therefore, it is necessary to formulate obstacle avoidance rules for each UAV. The strategy adopted in this study is to endow each UAV with the characteristics of the obstacles, including their position and size. When each UAV is flying towards its target, the other UAVs are regarded as moving obstacles.

In the UAV flight process, UAVs may avoid each other in certain cases. Considering the case shown in Figure 4 as an example, in a certain state, the target point of Wingman 1, which is on the left, is on the right, whereas the target point of Wingman 2, which is on the right, is the opposite, and both wingmen fly on the same horizontal plane. In this case, Wingman 1 must move in the positive direction of the $o_v y_v$ axis to get close to the target point, whereas Wingman 2 must move in the opposite direction. During flight, the distance between the two wingmen continuously decreases. When the distance is sufficiently small, the two wingmen perform an obstacle avoidance operation. Because of the particularity of this scene, the motion characteristics of the two wingmen are geometrically symmetrical, so they repeatedly avoid each other. As shown by the black dotted line track in Figure 4, the wingmen eventually have difficulties reaching the target points.

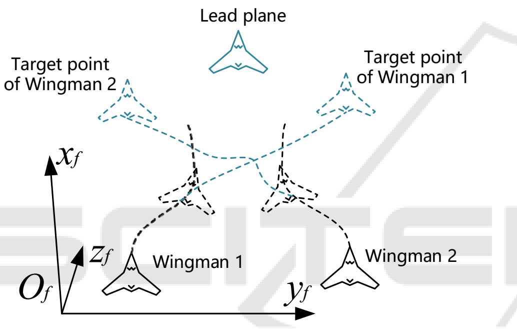

Figure 4: Mutual avoidance between wingmen.

To solve this problem, in this study, the avoidance strategy of formation members is designed by setting priority. In the initial setup, before the beginning of the planning, the members of the formation are numbered, and the order in which each UAV avoids the others is defined according to the principle that the priority decreases as the number increases. According to this rule, in the case shown in Figure 4, Wingman 1 only has to avoid the lead plane, whereas Wingman 2 has to avoid the captain and Wingman 1. Using this rule, the trajectories of the two wingmen entering the avoidance phase can be obtained, as shown by the blue dotted line in Figure 4.

5 SIMULATION RESULTS AND ANALYSIS

The formation designed in this study consisted of five fixed-wing UAVs, comprised of one lead plane and four wingmen. This stipulates that all UAVs are isomorphic (i.e., the performance is the same). The performance parameters are listed in Table 1.

Table 1: Performance Parameter.

Parameter Type	Value
UAVs'$R_o(m)$	50
Initial $v_l(m/s)$	100
$a_l(m/s^2)$	10 ($f_l > 0$) 40 ($f_l < 0$)
$a_\theta(rad/s)$	$\pi/6$
$a_\psi(rad/s)$	$\pi/6$
Speed range	$300 \geq v_l \geq 100(m/s)$ $\pi/6 \geq v_\theta \geq -\pi/6(rad/s)$ $\pi/6 \geq v_\psi \geq -\pi/6(rad/s)$

where R_o is the collision radius of the UAV, that is, the distance between the UAV and other obstacles must not be less than R_o; otherwise, it is considered that the UAVs have collided.

5.1 Simulation Experiment of the Kinematic Model of Fixed-wing UAV

In this section, the simulation experiments based on the fixed-wing UAV kinematics model proposed in this paper, carried out to verify the rationality of the trajectory planning results, are presented. In the mission scene of the experiment, after dynamic adjustment in the process of flying in the predetermined direction, the five fixed-wing UAVs fly to the new target area according to the newly specified formation.

Based on the traditional UAV kinematics model (Feng et al., 2021; Goerzen et al., 2010) and fixed-wing UAV kinematics model proposed in this paper, trajectory planning was carried out from the preset starting point, and the trajectories near the starting point of the UAV formation in three different initial scenes were obtained, as shown in Figure 5. The red circle in the picture is the starting point for the formation of the UAVs. It can be deduced from the figure that because the traditional UAV kinematics model only considers the position of the UAV in the constraints of the trajectory planning algorithm, the resulting track requires the UAV to turn from a large angle at the starting point of the planning. Considering the pink and yellow tracks in Figure 5(a) as an example, the initial direction of the planned flight trajectory deviates greatly from the original flight direction of the UAV, which is not in line with the actual flight situation of the fixed-wing UAV. However, the kinematics model proposed in this paper considers not only the position constraints of

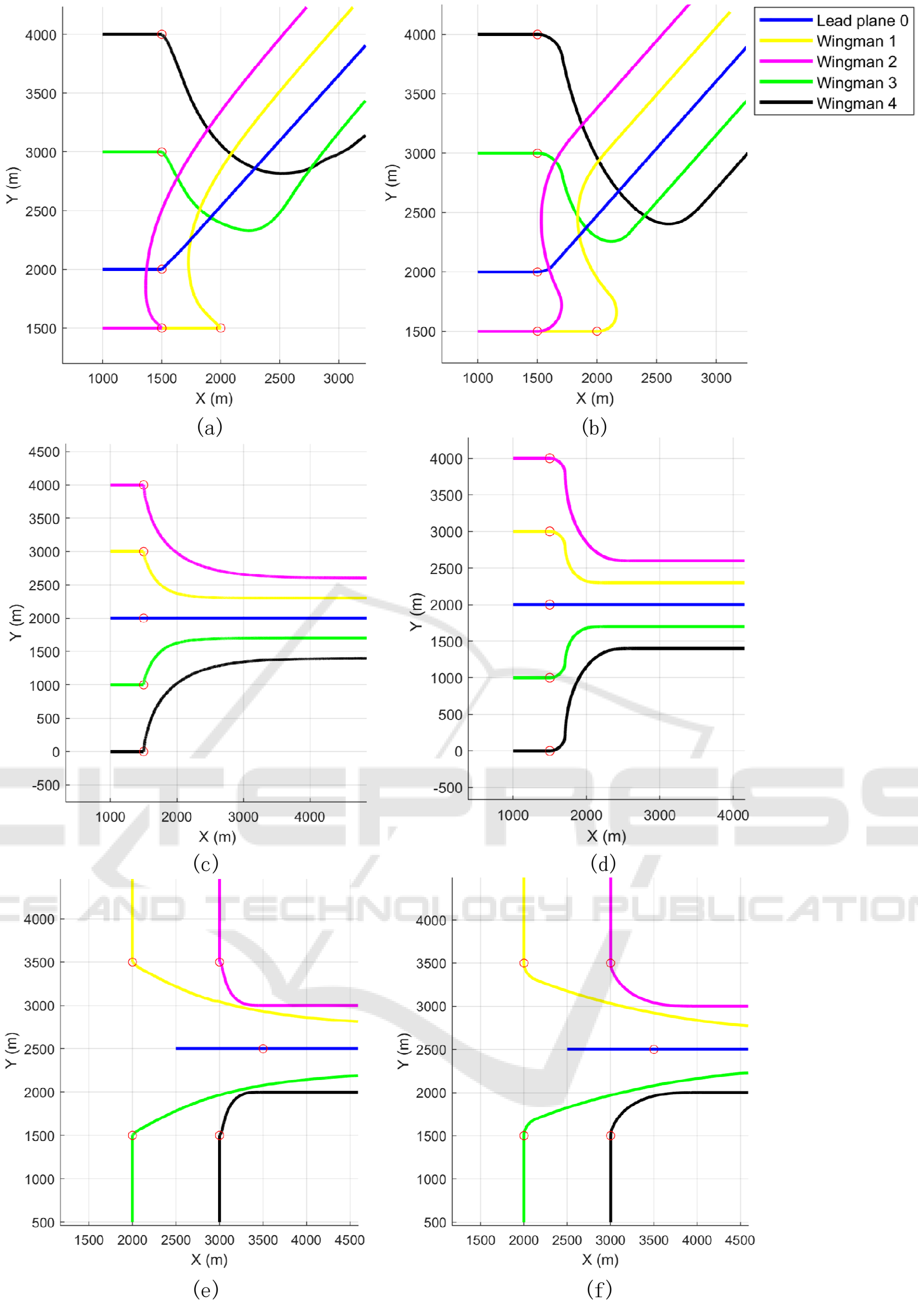

Figure 5: Trajectories generated based on the traditional model and the model proposed in this paper. (a, c, and e): traditional model; (b, d, and f): model proposed in this paper).

the UAV, but also the direction adjustment restrictions of the UAV; therefore, the resulting track is more continuous and more in line with the actual flight situation of the UAV

5.2 Simulation Experiment of the UAV Formation Cooperative Flight Model

This section presents the simulation experiments carried out in several scenes to verify the feasibility of the UAV formation cooperative flight model

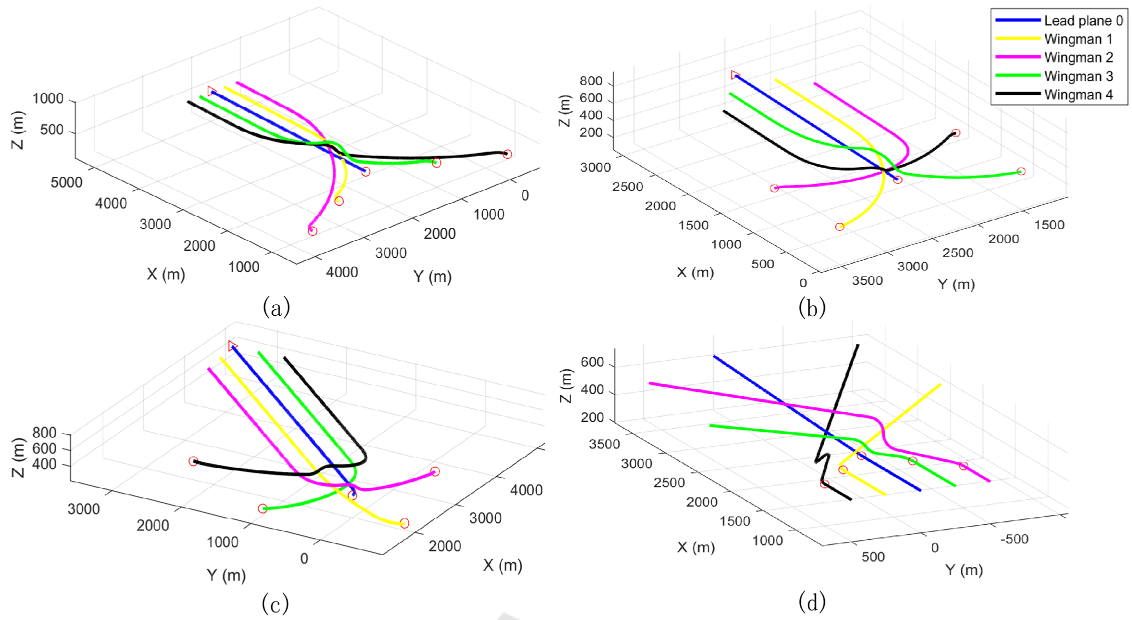

Figure 6: Trajectory planning based on the UAV formation cooperative flight model.

proposed in this paper, including teammates collision avoidance rules and formation flight ability.

Figure 6 shows the trajectory planning results of each fixed-wing UAV, from the specified starting point to the target point in four scenarios. Figures 6(a)–(c) show the trajectory planning results of the formation members from different starting points and directions. Figure 6(d) shows the flight trajectory planning results of the UAV formation flight from the original formation to their respective target points. From the figure, we can observe that the tracks of some formation members have crossed, which is a relatively common situation in the actual environment and requires the coordination of various UAVs to prevent interference or conflict in trajectory planning. The UAV formation cooperative flight model proposed in this paper sets priority rules for formation members to avoid conflict among them. Therefore, when planning based on the model, if there is a trajectory conflict, a flight path for avoiding the teammate is planned according to the priority order. As shown in Figure 6, the UAVs represented by different color tracks have different priorities; therefore, they avoid teammates that have proprieties higher than their own and form a specified formation or fly to their designated target area through a safe flight trajectory. This verifies the feasibility of the model proposed in this paper.

5.3 Comprehensive Simulation Experiment

In this section, the artificial potential field method is used to test the fixed-wing UAV kinematics model and UAV formation cooperative flight model proposed in this paper, thereby verifying that the planning results based on these models are feasible and can meet the collision avoidance requirements among teammates.

According to the performance parameters specified in Table 1, the flight trajectory planning results of the formation flight and decentralization process of five fixed-wing UAVs are shown in figure 7. Each UAV forms a target formation from the circle in the figure and then flies in formation for a period of time.

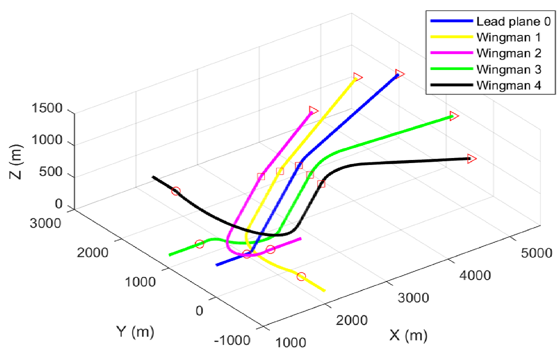

Figure 7: Formation flying and decentralization trajectory planning of UAVs.

Finally, the UAVs decentralize at the square box in the figure and fly to their respective target areas (triangle in the figure). As can be seen from the figure, the algorithm is solved based on the kinematics model for fixed-wing UAVs. Therefore, the generated trajectory considers the initial flight direction of each UAV, and the trajectory curve can better meet the constraints of the trajectory tracking for fixed-wing UAVs under actual conditions.

Figure 8 shows the distance between the wingmen and the target points during the formation flight stage. In this stage, the target point of each wingman is set by the multi-UAV formation cooperative model according to the position of the lead plane. As can be seen from the figure, the wingmen fly from their starting points to their respective target points. Eventually, all the wingmen form a target formation and continue to fly in formation with the lead plane.

Figure 9 shows the minimum distance among the members of the formation and other UAVs during the flight process. In the initial stage, the wingmen must adjust their flight direction at a large angle to assemble to the lead plane, so the distances among the members of the formation changes abruptly. Subsequently, the UAVs formed the designated formation, and the distances among the members of the formation remained stable. For approximately 25 s, as can be observed in the figure, the UAVs spread out and flew to their respective target areas.

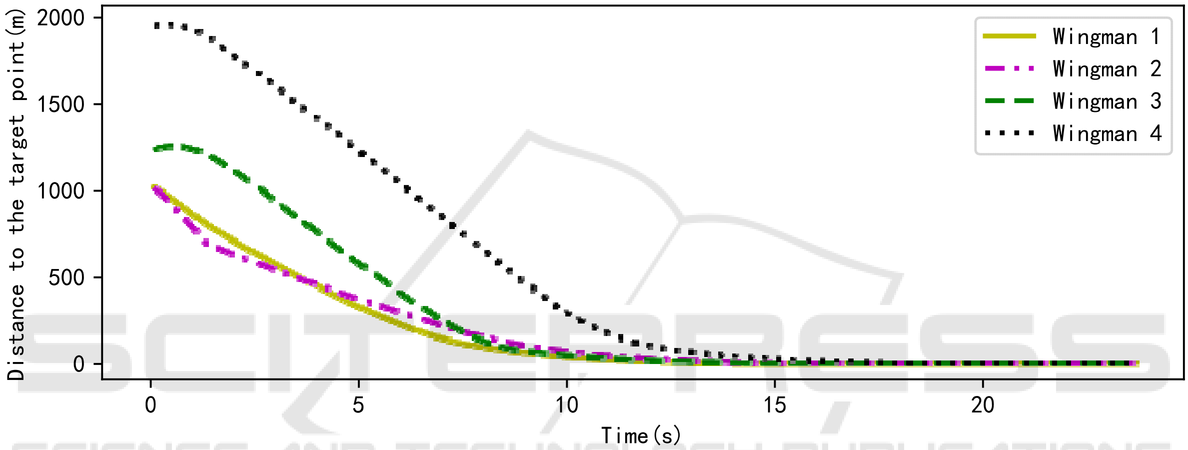

Figure 8: The situation of wingmen following the target points during the formation flight stage.

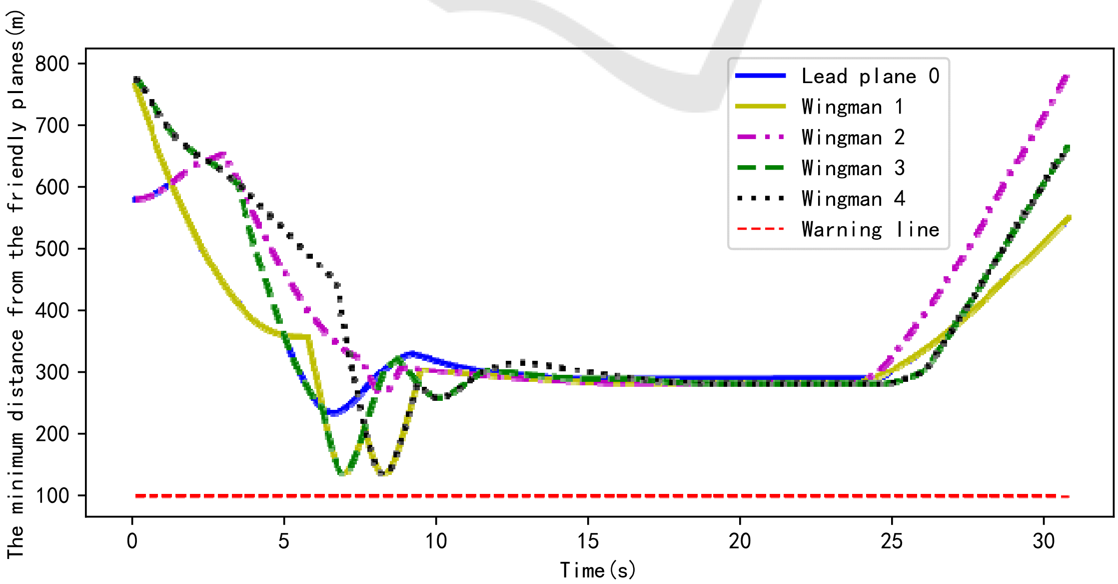

Figure 9: Minimum distance among formation members and teammates.

According to the setting in Table 1, the distances among the UAVs should not less than 100 m. The planning results show that the minimum distance between each UAV and teammates is more than 100 m (red dotted line in the figure) during the entire flight, and the UAVs can maintain a stable distance until the formation is broken.

Thus, it can be observed that the fixed-wing UAV kinematics model proposed in this paper can provide constraints for the trajectory planning algorithm and can meet the requirements of fixed-wing UAVs in a real environment. Furthermore, it can effectively provide the planning objectives and coordination strategies of each UAV for the trajectory planning algorithm, thereby improving formation flight and meeting the requirements for collision avoidance among teammates.

6 CONCLUSIONS

In this paper, considering the motion characteristics of fixed-wing aircraft, a kinematic model suitable for fixed-wing UAV was established. Subsequently, based on the formation structure of "Lead plane-Wingman", a UAV formation cooperative flight model was established. Through a comparative experiment with the traditional model, it was verified that the fixed-wing UAV kinematics model can better meet the motion constraints of the fixed-wing UAV. Through simulation experiments using multiple scenes, it was verified that the UAV formation cooperative flight model can provide a processing strategy for the cooperation and collision avoidance among UAVs. Finally, through a complex mission scene, it was verified that the planning results of a multi-UAV flight based on the model proposed in this paper can meet the flight trajectory feasibility and collision avoidance requirements among teammates during formation flight. The above experiments showed that the model proposed in this paper can provide the basis for the research on the formation flight trajectory planning of the fixed-wing UAV.

However, the influences of the complexity of the kinematics model and different collision avoidance priority combinations on the planning algorithm and planning results, respectively, were not investigated in this study. In the future work, optimization of the fixed-wing UAV formation model and a formation emergency handling strategy will be investigated.

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REFERENCES

Aggarwal, S., Kumar, N. (2020). Path planning techniques for unmanned aerial vehicles: A review, solutions, and challenges. *Computer communications*, 149, 270–299.

Bai, X., Jiang, H., Cui, J., Lu, K., Chen, P., Zhang, M. (2021). UAV path planning based on improved A∗ and DWA algorithms. *International journal of aerospace engineering*, 2021, 1–12. http://doi.org/10.1155/2021/4511252

Chen, Y., Yu, J., Su, X., Luo, G. (2015). Path planning for multi-UAV formation. *Journal of intelligent & robotic systems*, 77(1), 229–246. http://doi.org/10.1007/s10846-014-0077-y

Feng, J., Zhang, J., Zhang, G., Xie, S., Ding, Y., Liu, Z. (2021). UAV dynamic path planning based on obstacle position prediction in an unknown environment. *IEEE Access*, 9, 154679–154691. http://doi.org/10.1109/ACCESS.2021.3128295

Goerzen, C., Kong, Z., Mettler, B. (2010). A survey of motion planning algorithms from the perspective of autonomous UAV guidance. *Journal of intelligent and robotic systems*, 57(1–4), 65–100. http://doi.org/10.1007/s10846-009-9383-1

Gul, F., Mir, I., Abualigah, L., Sumari, P., Forestiero, A. (2021). A consolidated review of path planning and optimization techniques: Technical perspectives and future directions. *Electronics*, 10(18), 2250. http://doi.org/10.3390/electronics10182250

Huang, L., Qu, H., Ji, P., Liu, X., Fan, Z. (2016). A novel coordinated path planning method using k-degree smoothing for multi-UAVs. *Applied soft computing*, 48, 182–192. http://doi.org/10.1016/j.asoc.2016.06.046

Maini, P., Sujit, P. B. (2016). Path planning for a UAV with kinematic constraints in the presence of polygonal obstacles. *2016 International Conference on Unmanned Aircraft Systems (ICUAS)*.

Manathara, J. G., Ghose, D. (2012). Rendezvous of multiple UAVs with collision avoidance using consensus. *International journal of aerospace engineering* http://doi.org/10.1061/(ASCE)AS.1943

Phung, M. D., Ha, Q. P. (2021). Safety-enhanced UAV path planning with spherical vector-based particle swarm optimization. *Applied soft computing*, 107, 107376. http://doi.org/10.1016/j.asoc.2021.107376

Qadir, Z., Ullah, F., Munawar, H. S., Al-Turjman, F. (2021). Addressing disasters in smart cities through UAVs path planning and 5G communications: A systematic review. *Computer communications*, 168, 114–135. http://doi.org/10.1016/j.comcom.2021.01.003

Qiannan, Z., Ziyang, Z., Chen, G., Ruyi, D. (2014). Path planning of UAVs formation based on improved ant

colony optimization algorithm. *Paper presented at the, Yantai*.
Qu, Y., Zhang, Y., Zhang, Y. (2014). Optimal flight path planning for UAVs in 3-D threat environment. Paper presented at the.
Rajasree, R., Jisha, V. R. (2015). Optimal formation control of unmanned aerial vehicles with reconfiguration. *Paper presented at the 2015 International Conference on Control, Communication & Computing*, Trivandrum India.
Sahingoz, O. K. (2014). Generation of bezier curve-based flyable trajectories for multi-UAV systems with parallel genetic algorithm. *Journal of intelligent & robotic systems*, 74(1–2), 499–511. http://doi.org/10.1007/s10846-013-9968-6
Seiler, P., Pant, A., Hedrick, K. (2002). Analysis of bird formations. Paper presented at the.
Sharma, A., Shoval, S., Sharma, A., Pandey, J. K. (2021). Path planning for multiple targets interception by the swarm of UAVs based on swarm intelligence algorithms: A review. *Technical review* - IETE, 1–23. http://doi.org/10.1080/02564602.2021.1894250
Sivakumar, M., TYJ, N. M. (2021). A literature survey of unmanned aerial vehicle usage for civil applications. *Journal of aerospace technology and management*, 13 http://doi.org/10.1590/jatm.v13.1233
Tsourdos, A., White, B., Shanmugavel, M. (2011). Cooperative *Path Planning of Unmanned Aerial Vehicles*. A John Wiley and Sons, Ltd., Publication.
Wang, Y., Yue, Y., Shan, M., He, L., Wang, D. (2021). Formation reconstruction and trajectory replanning for multi-UAV patrol. *IEEE/ASME Transactions on Mechatronics*, 26(2), 719–729. http://doi.org/10.1109/TMECH.2021.3056099
Zhang, J., Yan, J., Zhang, P. (2018). Fixed-wing UAV formation control design with collision avoidance based on an improved artificial potential field. *IEEE Access*, 6, 78342–78351. http://doi.org/10.1109/ACCESS.2018.2885003
Zhu, X., Zhang, X., Yan, M., Qu, Y. (2017). Three-dimensional formation keeping of multi-UAV based on consensus. *Journal of central south university*, 24(6), 1387–1395. http://doi.org/10.1007/s11771-017-3543-4