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A Virtual Structure Formation Guidance Strategy for Multi-Parafoil Systems

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ABSTRACT The airdropping of multi-parafoil systems is of great significance to earthquake relief and military material transportation. In order to achieve the coordinated motion of multiple parafoils, a formation guidance strategy based on a virtual structure is proposed, which enables the formation of multiple parafoils to follow the planned trajectory and land at the target precisely. Firstly, since the main movement mode of a parafoil is turning and gliding, a multiphase homing trajectory for the reference point is planned, which mainly consists of a turning and gliding phase. Then, the trajectories of all the points on the virtual structure are generated by superimposing the relative positions of the virtual structure on the planned trajectory. Based on Lyapunov stability theory, a guidance strategy is designed to guide all parafoils to track the corresponding points on the virtual structure and complete the desired formation task. The simulation results show that the guidance strategy based on a virtual structure can effectively guide multiple parafoils to achieve coordinated formation movement. Parafoils dropped from different positions and heading angles can gradually gather together and form a formation, track the planned trajectories, land at the target point precisely and align up against the wind.

INDEX TERMS Virtual structure, formation, guidance, trajectory planning, parafoil.

I. INTRODUCTION

In military material supplies or earthquake relief operations, a large number of materials, such as weapons, ammunitions, medicine, drinking water, food and so on, need to be transported to the target point quickly to meet the needs of the task. Airdropping using parafoil to the target point becomes an effective choice for rapid material replenishment. For example, the U.S. military quickly airdropped desperately needed food and water to Haitian earthquake survivors, which greatly alleviate the suffering of people caused by the earthquake. The supplies are transported by the transport aircraft to a certain distance from the target point, and then all the supplies are delivered to the target point by parafoil or parachute.

Compared with the traditional circular parachute, the parafoil has the capability of gliding, controllability and a large load ratio. The flight direction and speed of a parafoil

can be adjusted by pulling down the parafoil control rope. When the control rope is pulled down by the left motor, the parafoil turns to the left and vice versa; when the control ropes are pulled down by the left and right motors simultaneously, the speed of the parafoil can be changed, which makes it possible to land at the target precisely. In addition, a parafoil can simulate the flare landing action of birds in the landing phase, which allows the parafoil to land more smoothly and gently. Therefore, in recent years, more and more researchers have become interested in replacing uncontrollable conventional parachutes with controllable parafoils to realize the delivery of large quantities of materials.

At present, there are two main ways to realize the airdropping of a large number of goods and materials. One way is to use a heavy cargo parafoil, which can deliver more goods and materials by increasing the canopy area of the parafoil and expanding the cargo platform. The area of the parafoil used in NASA's X-38 program, for example, is generally 7500 ft², and the maximum load capacity has reached

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about 25,000 lb (approximately 11 ton), which is basically at the upper limit. It is very difficult to further enhance the load capacity because the heavy cargo parafoil involves more complicated operations, such as a staged opening and parafoil reflex removal [1], which leads to a higher failure risk of airdrop mission.

Another method is to use multi-parafoil systems. The supplies can be delivered to the target point by multiple parafoils. This method has a better fault-tolerant performance. Even if one parafoil fails, the remaining parafoils can continue to complete the task, which increases the possibility of a successful airdrop. Meanwhile, this kind of airdrop method has good expandability, if more materials need to be delivered, a simple increase in the number of parafoils can satisfy the task requirement. Therefore, the study of multi-parafoil airdrops has more and more strategic significance, and has attracted the attention of many institutions including NASA and ESA, as well as a large number of scholars.

After multiple parafoils are dropped simultaneously, it is first necessary to ensure that all parafoils can reach the target area accurately and will not land at the wrong place; second, all parafoils should be dispersed within a small area to reduce the difficulty in goods and materials retrieval; third, the parafoils need to avoid collisions between each other during the flight to ensure their own safety; fourth, parafoils should align upwind when landing, in order to reduce landing impact and ensure the safety of the load; and finally, the parafoils need to form and maintain a formation. Therefore, it is obvious that compared with single parafoil airdropping, multi-parafoil airdropping needs to solve more problems, which makes the formation guidance of multi-parafoil systems more challenging. Multi-parafoil formation guidance refers to the process that achieves the following: when multiple parafoils are dropped from different positions and different heading angles, they gradually gather together from the scattered state, keep the relative position within a certain range, the formation of parafoils then follows a planned trajectory, and finally lands upwind to the target point. The formation shape of multi-parafoil systems can be changed by adjusting the distance between the parafoils and the specific point, called the reference point.

The commonly used formation methods include the leader-follower method, behaviour-based method and virtual structure method. In the leader-follower method, the leader sends information to the followers, and the followers follow the leader within a certain distance. Because of its simplicity and practicability, this method has been widely used in many applications, and a variety of cooperative formation results have been reported. The disadvantage of the leader-follower method is that the leader is less robust, and it is easy to have a single point failure problem; once the leader fails, the whole formation will be headless, leading to formation failure. The behaviour-based method refers to a set of basic behaviours of agents that are defined in advance, such as avoiding collision, avoiding obstacles, searching targets, formation keeping, trajectory tracking, etc. Then the control amount of the agents

can be obtained by calculating the weighted average of these basic behaviours. The difficulty of this method is the design of different basic behaviours and the determination of the weights of basic behaviours. Furthermore, this method is difficult to describe in mathematical form, which leads to difficulty in theoretical analysis and stability proof.

The virtual structure method defines the formation shape as a virtual rigid body, and the desired position of different agents is defined as a different reference point on virtual rigid body. The motion trajectory of a virtual structure is the reference trajectory of formation. The formation can be formed as long as the agents track the corresponding reference points on the virtual rigid body. There is no actual leader in the virtual structure method, which reduces the impact of the single point failure problem of the leader-follower formation method. In addition, the formation is regarded as a whole, therefore, the overall behaviour of the formation can be easily specified, and the task description can be simplified. At the same time, each agent only needs to track the corresponding points in the virtual structure, so the agent guidance strategy is easy to design. The leader-follower method, behaviour-based method and virtual structure method have their own advantages and disadvantages, this paper studies the virtual structure-based formation for use in multi-parafoil systems.

The contributions of this paper are as follows.

- 1) In contrast to traditional airdropping using heavy cargo parafoil or parachute, this paper develops multi-parafoil systems for the rapid transportation of massive goods and materials, which have stronger robustness, expandability, even if one parafoil fails, the rest of parafoils can continue to deliver the goods and materials to the target area.
- 2) This paper develops an optimal multiphase homing trajectory planning method by using simulated annealing algorithm, which is less likely to fall into local extremes. The planned trajectory consists of centripetal homing phase, energy management control phase and upwind landing phase, which can be easily tracked by the parafoils through turning, gliding and flare landing maneuvers, so the trajectory planning algorithm has high engineering practical value.
- 3) This paper proposes a novel formation guidance strategy for multi-parafoil systems based on virtual structure and provides a theoretical proof for the guarantee of stability. The proposed guidance strategy has good adaptability to a rapidly changing wind environment. This is a new contribution to the body of works since the majority of existing works does not address the formation guidance problem for multi-parafoil systems.

The structure of this paper is as follows. Section 2 gives the related research work. Section 3 gives the model of the multi-parafoil systems. The fourth presents the design of the desired multiphase homing trajectory for the virtual structure. The trajectory meets the requirements of small landing error and upwind landing. Then, the guidance strategy is designed for each parafoil, and the stability of the guidance strategy is

analysed. The simulation experiments are carried out and the simulation results are analysed in Section 5. Section 6 states the conclusion.

II. RELATED WORK

Many research results exist on aerodynamic coefficients, modeling and trajectory tracking of a single parafoil. Wu *et al.* [2] considered the influence of leading edge incision and trailing edge deflection, and studied the aerodynamic coefficients of a parafoil based on computational fluid dynamics. Li *et al.* [3] derived a linear system model of a parafoil on the basis of considering model variance and external disturbance. Tao *et al.* [4] studied parafoil path following in a windy environment based on generalized predictive control. Su *et al.* [5] studied the anti-disturbance constrained trajectory flight control for an ultra-low altitude airdrop system based on the barrier Lyapunov function. Luo *et al.* [6] proposed an accurate flight track control approach for a parafoil, which combined ADRC with wind feedforward compensation. The approach directly compensates the wind disturbance and improves the track tracking performance. The above researches on single parafoils greatly promote the development of parafoil technology and have given single parafoil strong trajectory tracking ability.

Research into multi-parafoil air-drop systems is still in its infancy, and the related research results are not yet sufficient. Kaminer *et al.* [7] firstly studied the coordinated transportation problem by using multiple parafoils with a high glide ratio. By planning a feasible collision-free path for each parafoil, each parafoil tracks the planned path precisely, and coordinated transportation is achieved. Inspired by flocking birds and swarming insects, Calise and Preston [8] mimicked the behavior of biological systems and improved the design of guidance and control systems for parafoil-based vehicles. Gurfil *et al.* [9] proposed a top-down guidance algorithm and cooperative task management method to solve the problem of accurate airdrop of emergency supplies in wide-scale disasters, which significantly improved the probability of a successful airdrop. Rosich and Gurfil [10] discussed the cooperative control strategy among multiple autonomous parafoils. By following the reference trajectory, behaviour-based rules were developed that control the relative motion of multiple parafoils. The research shows that multiple parafoils can experience safe separation between one other when headed for the same target, and all parafoils can follow the reference trajectory as a group. Luo *et al.* [11] proposed a trajectory planning and gathering strategy of multi-parafoil systems based on the Gauss pseudo-spectral method. The simulation results show that multiple parafoil systems can gradually gather into a flock and avoid collision between parafoils while steering to the target area. In [12], the author used an improved genetic algorithm to solve the multi-objective cooperative path planning problem for multi-parafoil systems. The simulation results show that the proposed method can plan feasible paths for multi-parafoil systems, and there is no collision between parafoils.

The research indicates that, the cooperative motion between parafoils can make airdrops more efficient and reliable for material transportation. Summarizing the existing works on multi-parafoil systems, we can find that the existing research results include the cooperative task management, behavior-based cooperative movement, etc., but the formation problem of multi-parafoil systems has not been solved yet.

In the research of virtual structure formation, Lewis *et al.* [13] proposed the idea of the virtual structure method for the first time, and successfully applied this formation strategy to a group of mobile robots, making all the robots move like particles embedded in a rigid structure. This method achieved high-precision formation. After this, the virtual structure was applied in different fields. Ren and Beard [14], [15] applied the virtual structure method to the formation flight of spacecraft. Even when communication between spacecrafts is strictly limited, multiple spacecraft can still form a formation under the guidance of the virtual structure method. Sadowska *et al.* [16] studied the formation control problem of unicycle mobile robots and proposed a distributed virtual structure control strategy with coupling among the robots. This method has better robustness to the disturbance of formation. Mehrjerdi *et al.* [17] used the virtual structure method to study the non-linear cooperative control of a group of mobile robots. By locating the position of the robot in the group, the robot can achieve trajectory tracking and establish an effective formation. The experimental results show that the algorithm is feasible. Askari *et al.* [18] studied the formation flight of unmanned aerial vehicles (UAVs) based on a virtual structure, and then designed the control law based on inverse dynamics. The simulation results show the effectiveness of the proposed control strategy. Li *et al.* [19] studied the formation path tracking problem of multiple unmanned underwater vehicles (UUVs) based on a virtual structure and leader formation control method. The simulation results show that all the UUVs can move in formation along the planned path at a given speed.

Generally speaking, there exists a lot of research results on single parafoils at present, but in the case of rapid transportation of large quantities of materials, multi-parafoil cooperative airdropping can better meet the requirements. Therefore, multi-parafoil airdropping has been gaining increasing attention, but few research results exist in this area. Current formation guidance algorithms mainly focus on mobile robots, unmanned aerial vehicles, aircraft, underwater vehicles, etc., while a formation guidance strategy suitable for parafoils is lacking; especially, the characteristics of a parafoil and the requirements of an airdrop task are not considered comprehensively. Trajectory tracking is the main control method of parafoil motion. If the trajectory tracking and cooperative formation can be combined comprehensively, it will be of great theoretical significance and practical engineering value. On the basis of previous studies, this paper works toward solving the problem of trajectory planning and virtual structure formation for multi-parafoil systems.

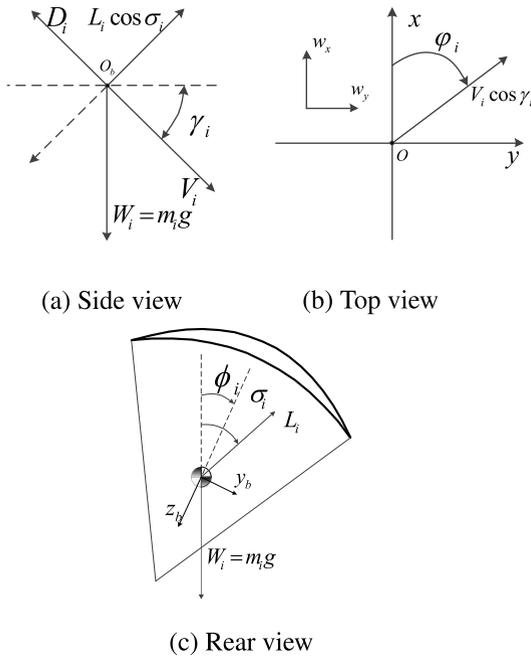


FIGURE 1. Force analysis diagram of a parafoil in flight.

III. SYSTEM MODELLING

A. PARAFOIL MODEL

The model of a single parafoil is presented in this section. Fig. 1 shows the three views of a parafoil. Through the force analysis of parafoil, the dynamics model is obtained as follows [7], [8], [20]:

$$\begin{cases} \dot{V}_i = g \left(-\frac{D_i}{m_i g} - \sin \gamma_i \right) \\ \dot{\phi}_i = \frac{g}{V_i \cos \gamma_i} \frac{L_i}{m_i g} \sin \sigma_i \\ \dot{\gamma}_i = \frac{g}{V_i} \left(\frac{L_i}{m_i g} \cos \sigma_i - \cos \gamma_i \right), \end{cases} \quad (1)$$

$$\begin{cases} \dot{x}_i = V_i \cos \gamma_i \cos \phi_i + w_x \\ \dot{y}_i = V_i \cos \gamma_i \sin \phi_i + w_y \\ \dot{z}_i = V_i \sin \gamma_i, \end{cases} \quad (2)$$

where, $i = 1, 2, \dots, N$. V_i , ϕ_i and γ_i is the respective speed, heading angle and glide angle of the parafoil i , (x_i, y_i, z_i) is the position coordinates of the parafoil in the inertial system, D_i and L_i is the drag and lift of the parafoil, respectively, m_i is the mass of the parafoil, g is the acceleration of gravity, σ_i is the bank angle of the parafoil, the speed constraint of each parafoil is $0 < V_{i \min} \leq V_i \leq V_{i \max}$, and the heading angle constraint is $|\phi_i| < \phi_{\max}$.

B. FORMATION ERROR MODEL

The formation configuration is defined by the virtual structure method in this paper. Assuming that there is a moving virtual structure reference point O_f , which flies along a given planning trajectory, then the formation coordinate system $O_f x_f y_f z_f$ can be defined with the reference point O_f as the

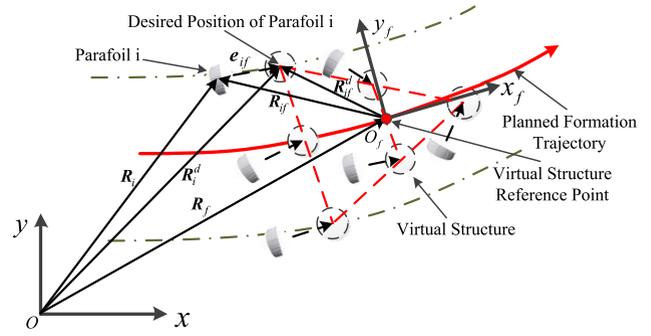


FIGURE 2. Virtual structure formation schematic diagram. The red dashed triangle represents the desired virtual structure. If every parafoil can track the corresponding point on the desired virtual structure, the formation can be formed.

origin. The direction of x_f is the projected direction of the velocity of the reference point O_f in the horizontal plane, y_f is perpendicular to x_f in the horizontal plane, and z_f is right-handed with x_f and y_f . Fig. 2 shows a schematic diagram of the parafoil virtual structure formation.

In Fig. 2, $R_i = (x_i, y_i, z_i)^T$ and $R_f = (x_f, y_f, z_f)^T$ is the position vector of parafoil i and virtual structure reference point in inertial coordinate system $Oxyz$, respectively, $R_{if} = (x_{if}, y_{if}, z_{if})^T$ is the relative position vector of parafoil i in the virtual structure formation coordinate system, and $R_{if}^d = (x_{if}^d, y_{if}^d, z_{if}^d)^T$ is the desired relative position vector in the virtual structure formation coordinate system. The formation can be determined by a set of relative position vectors $\left\{ (x_{if}^d, y_{if}^d, z_{if}^d)^T, i = 1, 2, \dots, N \right\}$, and N is the total number of parafoils. If $\lim_{t \rightarrow \infty} R_{if} \rightarrow R_{if}^d$ is confirmed, the parafoils can form the desired formation.

It is assumed that the motion characteristics of virtual reference points are given by the following differential equations based on time parameters:

$$\begin{cases} \dot{x}_f = V_f \cos \gamma_f \cos \phi_f \\ \dot{y}_f = V_f \cos \gamma_f \sin \phi_f \\ \dot{z}_f = V_f \sin \gamma_f \\ \dot{\phi}_f = \omega_f, \end{cases} \quad (3)$$

where ω_f is the heading angle velocity of the virtual reference point, and V_f , ϕ_f and γ_f is the speed, heading angle and glide angle of the virtual reference point. They are all piecewise continuous functions of time, whose values are given by the formation trajectory planning algorithm.

As can be seen from Fig. 2, the following vector relations are satisfied between R_i , R_f and R_{if} :

$$R_{if} = R_i - R_f. \quad (4)$$

Taking the derivative of equation (4) with respect to time, and converting the position error to the formation coordinate system, we can obtain the position error dynamic model in

formation coordinates:

$$\begin{cases} \dot{x}_{eif} = V_i \cos \gamma_i \cos \varphi_{ei} - V_f \cos \gamma_f + (y_{eif} + y_{if}^d) \omega_f \\ \dot{y}_{eif} = V_i \cos \gamma_i \sin \varphi_{ei} - (x_{eif} + x_{if}^d) \omega_f \\ \dot{z}_{eif} = V_f \sin \gamma_f - V_i \sin \gamma_i, \end{cases} \quad (5)$$

where the superscript d indicates that the parameter is the desired value. $\varphi_{ei} = \varphi_i - \varphi_i^d$ is the heading angle error, $x_{eif} = x_{if} - x_{if}^d$, $y_{eif} = y_{if} - y_{if}^d$, and $z_{eif} = z_{if} - z_{if}^d$ is the formation position error. $V_i \cos \gamma_i$ is the speed of parafoil i in the horizontal plane, and $V_f \cos \gamma_f$ is the speed of the virtual reference point in the horizontal plane. The virtual structure formation guidance problem of multi-parafoil systems can be summarized as follows: given a set of reference signals R_{if}^d and the initial position error $[x_{eif}(0), y_{eif}(0), z_{eif}(0)]^T$ of the system, the guidance strategy is designed for each parafoil i , such as V_i , φ_i and γ_i , to make the relative position error converge to 0, i.e., $\lim_{t \rightarrow 0} \|[x_{eif}, y_{eif}, z_{eif}]^T\| = 0$.

IV. THE DESIGN OF GUIDANCE STRATEGY FOR FORMATION

In order to achieve the formation airdrop of multi-parafoil systems, this paper separately designs the multiphase homing trajectory, the virtual structure formation reference trajectories and the formation guidance strategy. The system structure is shown in Fig. 3. Firstly, The trajectory planning algorithm plans the multiphase homing trajectory for the reference point. Next, the relative positions of the virtual structure are superimposed on the planned trajectory, which ensures that the virtual structure flies along the planned trajectory. In this way, the desired virtual structure formation reference trajectories for all the parafoils are generated in the inertial coordinate system. Finally, the formation guidance law is designed to ensure that each parafoil tracks its desired position in the inertial coordinate system; if each parafoil can track the desired position, a formation can be formed. From the architecture diagram, we can see that the virtual structure-based formation belongs to a centralized formation, and the advantage is that there is no actual leader. Furthermore, there is no need for communication between parafoils, which reduces the cost of communication.

A. MULTIPHASE HOMING TRAJECTORY PLANNING

Trajectory planning is the key of multi-parafoil systems to achieve precise airdrop. It refers to finding a feasible and accurate trajectory from the airdrop release point to the designated target point according to the requirements of the airdrop mission. Trajectory planning algorithm provides reference signals for the guidance strategy. Based on the obtained flight trajectory, the appropriate guidance strategy and parameters can be designed to generate guidance output and guide the parafoils to accurately track the planned trajectory and land at the designated target point.

Taking into account the characteristics of parafoil in this section, the parafoil multiphase homing trajectory is

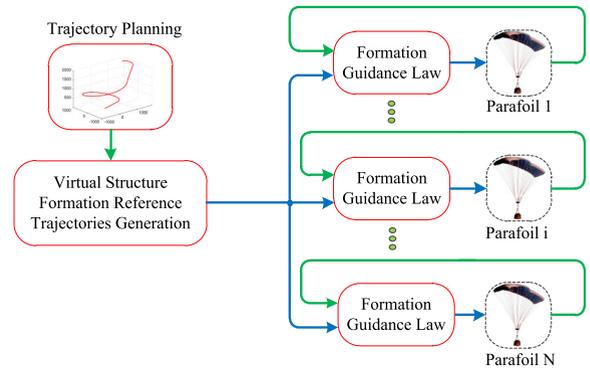


FIGURE 3. Architecture diagram of a virtual structure formation airdrop.

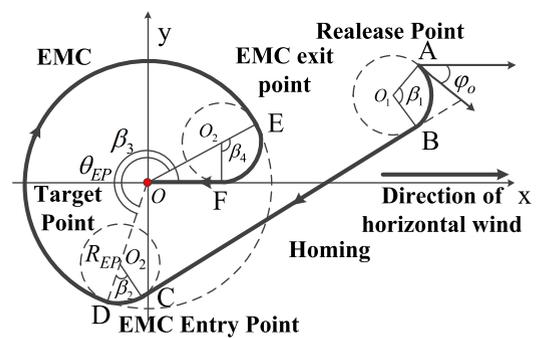


FIGURE 4. Horizontal projection diagram of a multiphase homing trajectory. Point A is the airdrop release point, φ_0 is the initial heading angle of parafoil, point O is the landing target point, and the phase AB, CD and EF is the turning transition phase. Phase BC is the centripetal homing—the parafoil glides to the target area through the centripetal homing flight. Phase DE is the energy management control phase—the parafoil consumes height by spiral. Phase FO is the upwind landing phase—assuming that the direction of the wind field is along the x-axis, the parafoil will fly upwind to the landing target point.

designed. A parafoil system can mainly perform turning, gliding, flare landing and other manoeuvre operations, and the multiphase homing method makes full use of these characteristics. The planned trajectory mainly includes a turning phase, straight gliding phase and so on, so this is easy to realize in engineering terms. Therefore, this paper uses the multiphase homing method to provide a reference trajectory for formation. The multiphase homing trajectory can be roughly divided into a centripetal homing phase, energy management control phase and upwind landing phase. Its horizontal projection is shown in Fig. 4.

In Fig. 4, the key to determine the whole multiphase trajectory is the parameters (R_{EP}, θ_{EP}) of entry point D, where R_{EP} is the radius of the energy management control phase and θ_{EP} is the angle of the entry point. On the one hand, the value of R_{EP} should be larger than the minimum turning radius, yet on the other hand, it should not be too large, so as to avoid affecting the landing accuracy. By optimizing the parameters of the entry point, the optimized multiphase trajectory can be determined. The quality of the trajectory can be reflected by the optimization objective function.

The function selected in this paper is shown in Equation (6). The optimization objective is to minimize the horizontal deviation between the actual landing point and the planned target point of the homing trajectory:

$$J = R_{\min}(\beta_1 + \beta_2 + \beta_4) + R_{EP}\beta_3 + (\|\vec{BC}\| + \|\vec{FO}\|) - z_0/|\tan\gamma|, \quad (6)$$

where $R_{\min}(\beta_1 + \beta_2 + \beta_4)$ is the total length of the transition phase, $R_{EP}\beta_3$ is the length of the energy management control phase, $(\|\vec{BC}\| + \|\vec{FO}\|)$ is the total length of the gliding phase, and $z_0/|\tan\gamma|$ is the horizontal flight distance of the parafoil.

Next, the geometric relationship of the homing trajectory in Fig. 4 is analyzed. The initial position of the parafoil is (x_0, y_0, z_0) and the initial heading angle is φ_0 , then the location of O_1 is

$$\begin{bmatrix} x_{O_1} \\ y_{O_1} \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + R_{\min} \begin{bmatrix} \cos(\varphi_0 - \pi/2) \\ \sin(\varphi_0 - \pi/2) \end{bmatrix}. \quad (7)$$

The location of O_2 is

$$\begin{bmatrix} x_{O_2} \\ y_{O_2} \end{bmatrix} = (R_{EP} - R_{\min}) \begin{bmatrix} \cos\theta_{EP} \\ \sin\theta_{EP} \end{bmatrix}. \quad (8)$$

We can see that the length of $\|BC\|$ is equal to $\|O_1O_2\|$. The angle β_1 of the first transition arc can be expressed as

$$\beta_1 = \angle\vec{BC} - \varphi_0 = \arctan \frac{y_{O_2} - y_{O_1}}{x_{O_2} - x_{O_1}} - \varphi_0. \quad (9)$$

The angle β_2 of the second transition arc can be expressed as

$$\beta_2 = \theta_{EP} - \angle\vec{BC} - \pi/2 = \theta_{EP} - \arctan \frac{y_{O_2} - y_{O_1}}{x_{O_2} - x_{O_1}} - \pi/2. \quad (10)$$

The central angle β_3 of the arc in the energy management control phase can be expressed as

$$\beta_3 = \arcsin \frac{R_{\min}}{R_{EP} - R_{\min}} - \theta_{EP}. \quad (11)$$

The angle β_4 of the last transition arc can be expressed as

$$\beta_4 = \arcsin \frac{R_{\min}}{R_{EP} - R_{\min}} + \pi/2. \quad (12)$$

The design problem of a multiphase homing trajectory can be transformed into the parameter optimization problem of the objective function by using the above geometric relationship. We can choose an appropriate optimization algorithm to determine the optimized parameters of the entry point, then the optimal multiphase homing trajectory shown in Fig. 4 can be obtained by these parameters. The simulated annealing algorithm is insensitive to the initial value and can effectively avoid falling into a local optimum. Therefore, this paper chooses a simulated annealing algorithm to optimize the parameters of the entry point.

A simulated annealing algorithm is a heuristic algorithm that was proposed by Kirkpatrick et al. [21] in 1983. The algorithm simulates the process of metal heating and cooling in

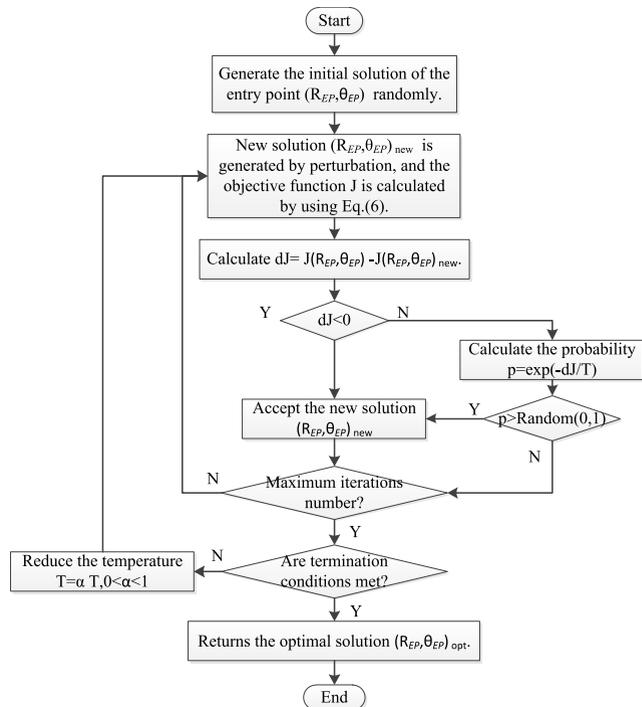


FIGURE 5. Flow chart of the simulated annealing algorithm.

metallurgy. The ions of high temperature metal contain a lot of energy and have the ability of random movement. With the temperature decreasing gradually (annealing), if the temperature reaches a certain value, the ions will be in the state of thermal equilibrium, and when the metal is completely cooled, the system will be in the state of low energy. The basic implementation process of the simulated annealing algorithm is as follows. Firstly, an initial solution of the problem to be solved is given, and the temperature value is set to a higher value. Then, a random disturbance is superimposed with the current solution to generate a new solution, and the energy changes of the two solutions are compared to determine whether or not to accept the new solution. If the energy is decreasing according to the new solution, the algorithm accepts the new solution directly. If the energy is increasing, the algorithm accepts the new solution with a higher probability at high temperature of jumping out of the local minimum region, but the possibility of acceptance will decrease with the decreasing of temperature, until the algorithm no longer accepts the new solution at the lowest temperature. The optimal solution is produced in such a case. The energy is calculated by Equation (6). Fig. 5 shows the flow chart of the simulated annealing algorithm.

Given the initial position of (x_0, y_0, z_0) , the initial velocity of V_0 , the initial heading angle of φ_0 and the range of turning radius $[R_{\min}, R_{\max}]$, etc., the parameters of the entry point can be optimized by the simulated annealing algorithm. And then, the trajectory of the virtual structure reference point can be determined by substituting the geometric relationship shown in Fig. 4 into Equation (3).

B. VIRTUAL STRUCTURE FORMATION REFERENCE TRAJECTORIES GENERATION

After planning the reference point trajectory, the desired trajectories of the points on the virtual structure need to be generated, and then each parafoil can track the desired trajectory of the corresponding point to achieve the goal of formation cooperative movement. By using this virtual formation guidance method, the formation problem is transformed into a trajectory tracking problem of a single parafoil, and then the trajectory tracking can be implemented by using the following designed non-linear guidance law.

When the planning trajectory is given, the state vector $(x_f, y_f, z_f)^T$ of the virtual structure formation reference point is known. By converting the desired distance vector $R_{if}^d = (x_{if}^d, y_{if}^d, z_{if}^d)^T$ of each virtual point in the formation coordinate system to the inertial coordinate system, and then superposing the result to the formation reference point, we can obtain all the desired trajectories for each parafoil:

$$\begin{bmatrix} x_i^d \\ y_i^d \\ z_i^d \end{bmatrix} = \begin{bmatrix} x_f \\ y_f \\ z_f \end{bmatrix} + \begin{bmatrix} \cos\varphi_f & \sin\varphi_f & 0 \\ -\sin\varphi_f & \cos\varphi_f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{if}^d \\ y_{if}^d \\ z_{if}^d \end{bmatrix}. \quad (13)$$

C. VIRTUAL STRUCTURE FORMATION GUIDANCE LAW DESIGN AND STABILITY ANALYSIS

The formation guidance law is designed by using the errors between the current position and the desired position of the parafoil to ensure that each parafoil can track its corresponding virtual structure points. Then, the parafoil is adjusted to the desired formation position to achieve the goal of formation cooperative airdrop. The guidance law is derived based on the Lyapunov stability theory in this paper so that $(x_{eif}, y_{eif}, z_{eif}) \rightarrow 0$. The Lyapunov function is defined as follows:

$$V_{Ly_i} = \frac{1}{2} (x_{eif}^2 + y_{eif}^2 + z_{eif}^2). \quad (14)$$

Taking the derivative of Equation (14), and substituting Equation (5) into the derivative, we can obtain the following results:

$$\begin{aligned} \dot{V}_{Ly_i} = & (V_i \cos\gamma_i \cos\varphi_{ei} - V_f \cos\gamma_f + y_{if}^d \omega_f) x_{eif} \\ & + (V_i \cos\gamma_i \sin\varphi_{ei} - x_{if}^d \omega_f) y_{eif} + (V_f \sin\gamma_f - V_i \sin\gamma_i) z_{eif}. \end{aligned} \quad (15)$$

When the derivative of the Lyapunov function is less than 0, the formation error tends to be zero if the following equation can be held:

$$\begin{cases} V_i \cos\gamma_i \cos\varphi_{ei} = V_f \cos\gamma_f - y_{if}^d \omega_f - k_1 x_{eif} \\ V_i \cos\gamma_i \sin\varphi_{ei} = x_{if}^d \omega_f - k_2 y_{eif} \\ V_f \sin\gamma_f = V_i \sin\gamma_i - k_3 z_{eif}, \end{cases} \quad (16)$$

where k_1, k_2 and k_3 are greater than 0, substitute Equation (16) into Equation (15), and we can get

$$\dot{V}_{Ly_i} = - (k_1 x_{eif}^2 + k_2 y_{eif}^2 + k_3 z_{eif}^2) < 0. \quad (17)$$

By solving Equation (16), we can get

$$\begin{cases} V_i^{com} = \left((V_f \cos\gamma_f - y_{if}^d \omega_f - k_1 x_{eif})^2 + (x_{if}^d \omega_f - k_2 y_{eif})^2 + (V_i \sin\gamma_i - k_3 z_{eif})^2 \right)^{\frac{1}{2}} \\ \varphi_i^{com} = \varphi_i + \arctan \frac{x_{if}^d \omega_f - k_2 y_{eif}}{V_f \cos\gamma_f - y_{if}^d \omega_f - k_1 x_{eif}} \\ \gamma_i^{com} = \arcsin \frac{V_i \sin\gamma_i + k_3 z_{eif}}{V_i^{com}}. \end{cases} \quad (18)$$

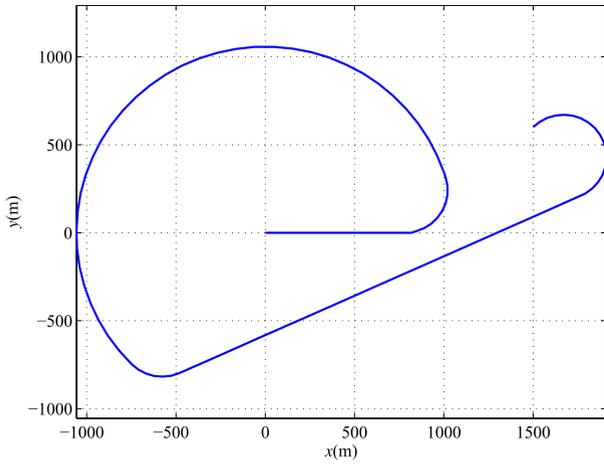
Equation (18) is the guidance command for parafoil i . Considering Lyapunov function (14), the derivative (15) of the Lyapunov function is obtained. If the guidance instruction of equation (18) is substituted into Equation (15), the derivative Equation, (17), is established. Therefore, according to the Lyapunov theory, the formation error $(x_{eif}, y_{eif}, z_{eif})$ will tend to zero, formation is formed, and the system is stable. By substituting the guidance commands $V_i^{com}, \varphi_i^{com}$ and γ_i^{com} into equation (2), we can get v_{x_i}, v_{y_i} and v_{z_i} , and then we can get the control inputs u_{x_i}, u_{y_i} and u_{z_i} by taking the derivative of the velocity.

Remark 1: In the formation guidance strategy framework based on virtual structure, each virtual individual of the virtual structure corresponds to the desired state of a actual parafoil. If we can find a lyapunov function and design a stable controller for each parafoil, the controller will make each parafoil tend to its own desired state, the position error between the actual position and the desired position will tend to 0, and a formation which consistent with the virtual structure can be formed. The controller designed in this paper is based on the lyapunov stability theory, the lyapunov function found is positive definite, and its derivative is negative definite, so the error system is stable. Even though there are initial errors and random wind interference, all the parafoils can track their desired state.

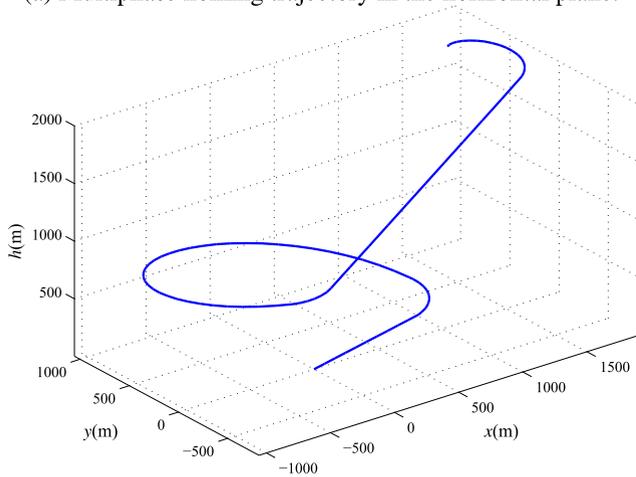
V. SIMULATION EXPERIMENTS AND ANALYSIS

In order to validate the effectiveness of the virtual structure formation algorithm, a numerical simulation was carried out with six parafoils. Firstly, the multiphase homing trajectory is planned for the virtual structure reference point. Note that the influence of constant wind field is considered as the initial offset of the reference point in this paper. The initial position of the reference point is (1500m, 600m, 2000m), the initial speed is $V_0 = 25$ m/s, and the initial heading angle is 45° . The parameters of the simulated annealing algorithm are set as follows: the range of R_{EP} is $[R_{min}, R_{max}] = [800m, 1500m]$, the initial solution is set to $(1000, 3\pi/4)$. The optimal parameters of the entry point obtained by simulated annealing algorithm are $(R_{EP}, \theta_{EP})_{opt} = (1057.4m, -135^\circ)$, and the planned multiphase homing trajectory is shown in Fig. 6.

As can be seen from Fig. 6, the planned trajectory can meet the requirement of a precise airdrop, and it can also achieve an upwind landing. In addition, the planned trajectory is a combination of straight lines and arcs, so the parafoil can



(a) Multiphase homing trajectory in the horizontal plane.



(b) Multiphase homing trajectory in 3-D space.

FIGURE 6. Multiphase homing trajectory planned results for the virtual structure reference point.

track the trajectory by gliding and turning, and the control motors of the parafoil do not need to adjust the control rope frequently.

In this paper, the desired virtual structure formation shape is a triangle, the formation vectors are taken as $(x_{1f}^d, y_{1f}^d, z_{1f}^d) = (60, 0, 0)$, $(x_{2f}^d, y_{2f}^d, z_{2f}^d) = (0, 60, 0)$, $(x_{3f}^d, y_{3f}^d, z_{3f}^d) = (0, -60, 0)$, $(x_{4f}^d, y_{4f}^d, z_{4f}^d) = (-60, 120, 0)$, $(x_{5f}^d, y_{5f}^d, z_{5f}^d) = (-60, 0, 0)$, $(x_{6f}^d, y_{6f}^d, z_{6f}^d) = (-60, -120, 0)$, and the reference point of the virtual structure is located at $(0, 0, 0)$. The triangle formation is shown in Fig. 7. It can be seen that the spacing between the structural points has two values, one is 120 m, the other is $60\sqrt{2}$ m, that is, the minimum spacing between parafoils is $60\sqrt{2}$ m, which is about 84.9 m.

The virtual structure reference point (x_f, y_f, z_f) moves along the planned trajectory, and then according to Equation (13), the desired trajectories of the virtual structure can be generated as shown in Fig. 8. The formation shape can be drawn by connecting the desired position at the same

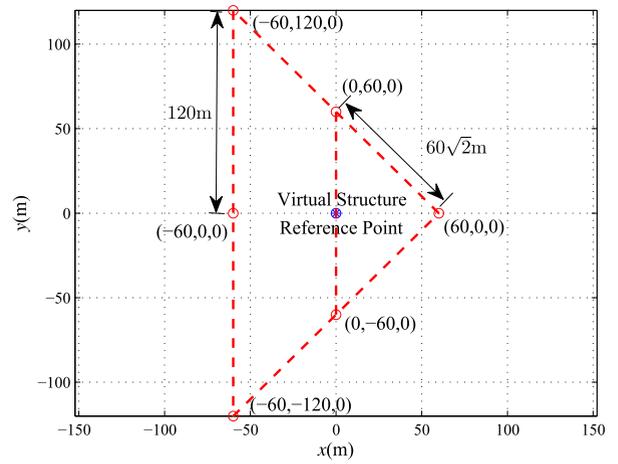


FIGURE 7. Desired formation shape virtual structure.

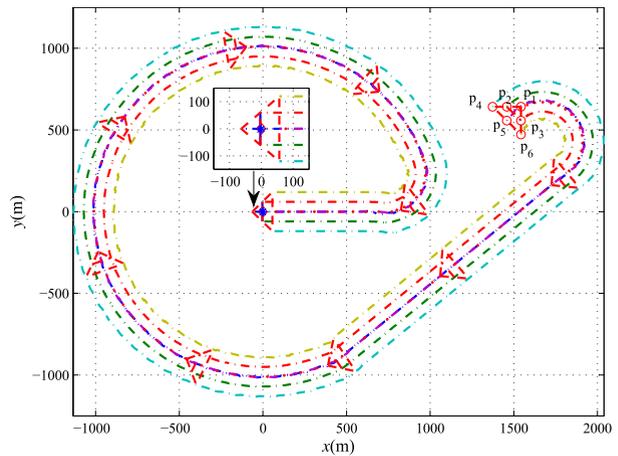


FIGURE 8. The generated formation desired trajectories of virtual structure.

TABLE 1. The initial states for the parafoils.

Para. No.	Initial coordinate	angle
1	(1600, 700, 1900)	45°
2	(2100, 800, 2000)	65°
3	(600, 1500, 2000)	80°
4	(1800, 900, 2000)	75°
5	(500, 1900, 2000)	105°
6	(800, 1300, 2000)	95°

moment. It can be seen that the formation shape of the virtual structure maintains a triangle in the process of moving along the planned trajectory.

The initial airdrop states of the parafoils are shown in Tab. 1. The velocity constraint is $V_{i\min} = 18.8$ m/s, $V_{i\max} = 32$ m/s, the gain of guidance law is $k_1 = 0.4$, $k_2 = 0.5$ and $k_3 = 0.5$.

The wind can be regarded as an interference, which has a great influence on the motion characteristics of parafoil, therefore, it is necessary to test the anti-interference performance of the guidance law. Wind is usually composed of

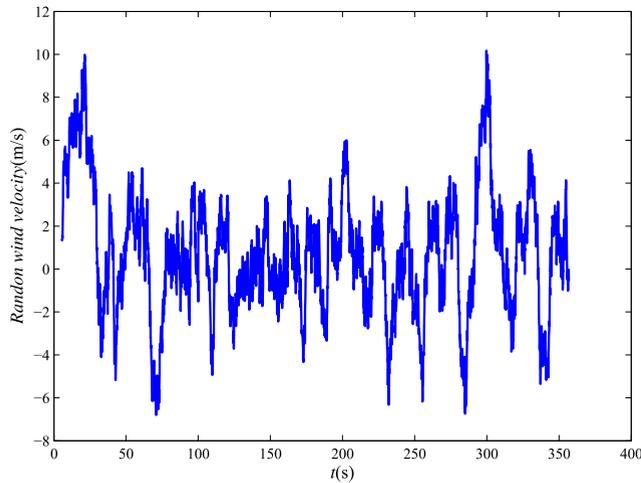


FIGURE 9. The random wind with meaning value of 0 m/s and standard deviation of 2 m/s.

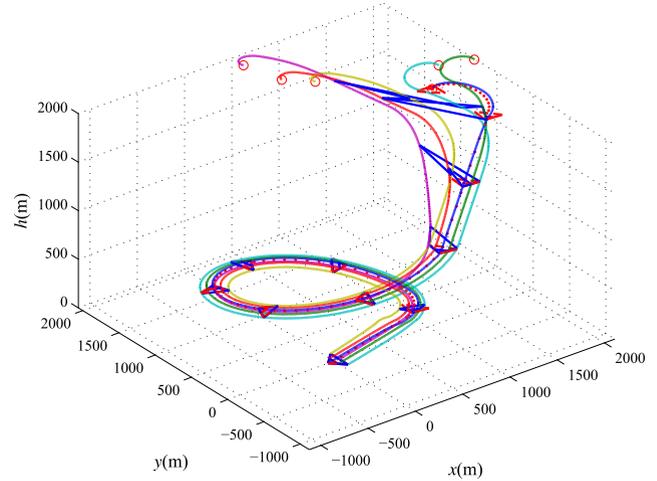


FIGURE 11. The virtual structure-based formation process of multi-parafoil systems in the 3-D space with the random wind.

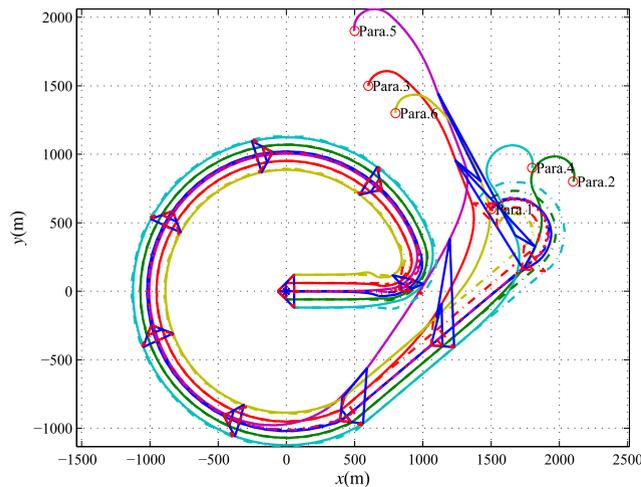


FIGURE 10. The virtual structure-based formation process of multi-parafoil systems in the horizontal plane with the random wind.

constant wind and random wind. In general, the influence of constant wind is converted into the initial position deviations of the parafoils, so only the random wind needs to be considered. As shown in Fig. 9, a Gaussian random wind with a meaning value of 0 m/s and a standard deviation of 2 m/s are added to the multi-parafoil systems.

Under the guidance law, each parafoil tracks the corresponding reference points in the virtual structure, thus obtaining the formation trajectories of multi-parafoil systems in the plane as shown in Fig. 10. Connecting the position of each parafoil at the same moment (the blue solid line in the figure), we can get the actual formation.

As we can see from the figure, each parafoil is at a certain distance from their own reference points at the beginning. There is no formation formed between the parafoils at this time. But with the guidance law, we can notice that, even if there is random wind interference during the whole airdrop process, the parafoils gradually catch up with the reference point and the formation is formed basically at the end of the

centripetal homing phase. In the energy management control phase, the actual formation (blue solid line) almost coincides with the virtual structure (red dashed line). It is evident that the guidance law designed in this paper can make the parafoil track the trajectory of the virtual structure accurately and realize formation flight of multiple parafoils. Note that in the process of transition from the energy management control phase to the final landing phase, due to the transition from turning flight to straight gliding, the actual formation is different from the virtual structure. But after the transition, the formation returns to normal and upwind lands to the target point. The simulation results show the effectiveness of the proposed formation method in this paper.

Fig.11 shows the motion trajectories of several parafoils in 3-D space. It can be seen that the parafoils dropped from different positions and directions are scattered in the initial stage, but under the guidance law, the parafoils start to adjust the flight direction and gradually become close to each other, then begin to execute centripetal flight and form a triangular formation. The altitude is consumed by hovering at the energy management control phase, then the parafoils begin to fly in a straight line and land at the target point. We can see that the scattering of the parafoils is much smaller at this point than that at the beginning; all parafoils land near the target point (0, 0, 0). The precise airdrop of the multi-parafoil systems is achieved and the landing dispersion is reduced. Fig. 12 shows the corresponding curves of control inputs for each parafoil during the formation flight process.

Fig. 13 is the formation error curve in the formation process when $k_1 = 0.4$, $k_2 = 0.5$, $k_3 = 0.5$. It can be seen that in the initial stage, each parafoil is far from its desired target, so the initial error is large. But under the guidance law designed in this paper, the formation error gradually decreases. At about 150 s, the formation error basically decreases to 0 m, each parafoil traces its virtual structure reference points and the formation is formed. Note that the formation error increases suddenly, as previously mentioned,

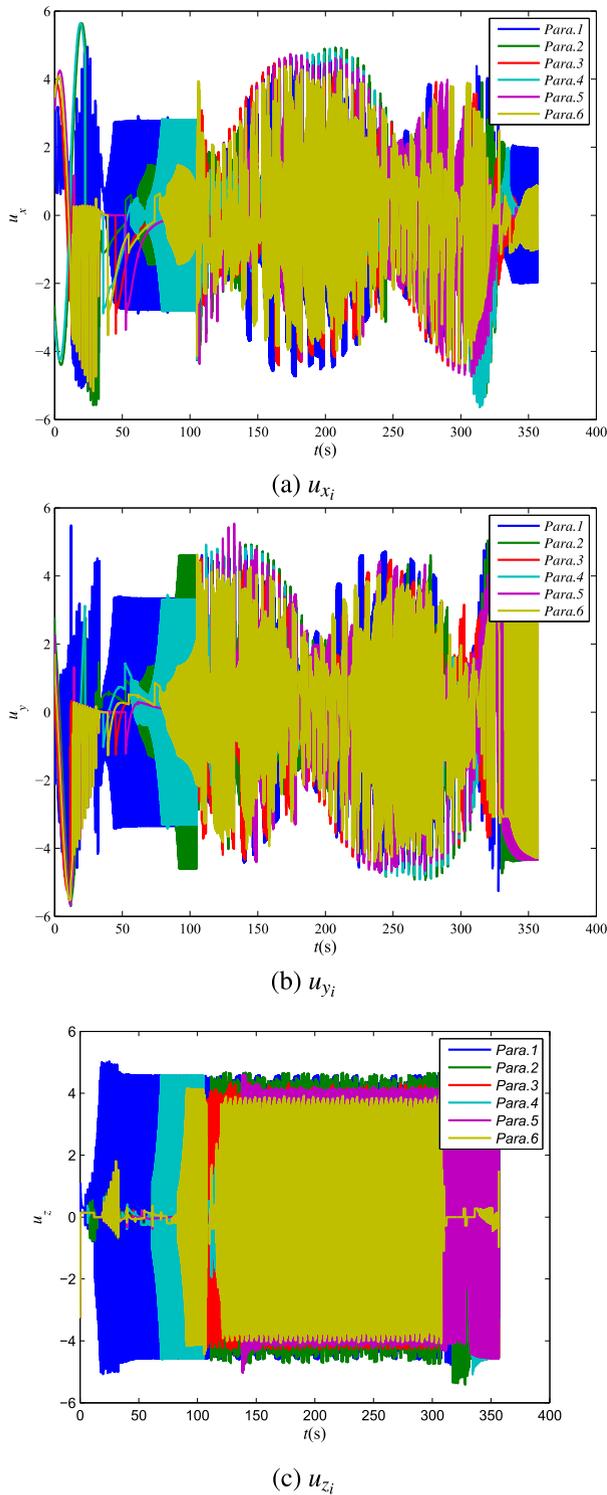


FIGURE 12. Control inputs of all the parafoils.

at about 330 s, the parafoils underwent a transition from the energy management control phase to the final landing phase, but the formation error reduces to about 0 m before the final landing.

The coefficients k_1 , k_2 and k_3 in the guidance law have a certain influence on the stable time of the multi-parafoil

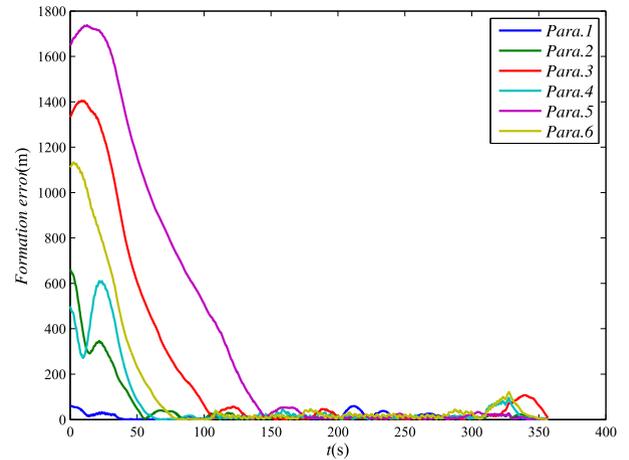


FIGURE 13. Formation error curve with the random wind when $k_1 = 0.4$, $k_2 = 0.5$, $k_3 = 0.5$.

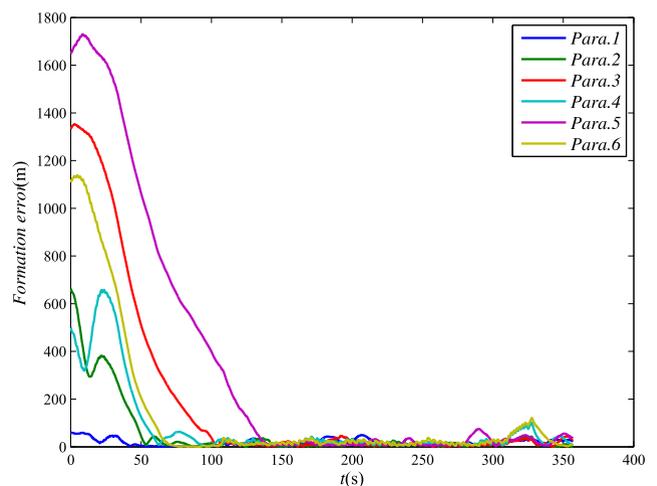


FIGURE 14. Formation error curve with the random wind when $k_1 = 0.4$, $k_2 = 1$, $k_3 = 0.5$.

systems. When the coefficients k_1 , k_2 and k_3 are increased, the time for the system to reach stability will be shortened, but the steady-state error will increase. For example, when $k_1 = 0.4$, $k_2 = 0.5$, $k_3 = 0.5$, the stable time is about 150 s. By analyzing and calculating the simulation experimental data, it can be found that the average steady-state error between actual value and desired value for all the parafoils is 11.1960 m. When $k_1 = 0.4$, $k_2 = 1$, $k_3 = 0.5$, as shown in Fig. 14, the stable time for the multi-parafoil systems is reduced to about 145s, however, the average steady-state error between the actual value of each parafoil and the desired value is increased to 13.5240 m. Therefore, when choosing the coefficients of guidance law, a compromise should be made between shortening the stable time and reducing the average steady-state error. At the same time, it should be noted that k_1 , k_2 and k_3 cannot be selected too large, otherwise the control quantity may be saturated.

Fig. 15 is the separation distance curve between parafoils. It can be seen that the distance between parafoils is large

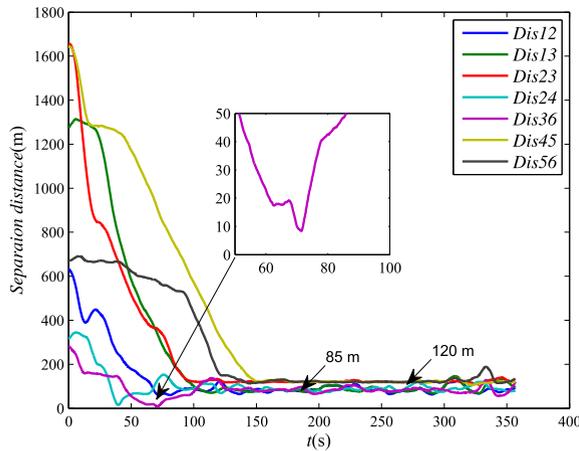


FIGURE 15. Separation distance curve between parafoils with the random wind.

at the beginning. But the distance decreases gradually and the parafoils begin to glide close to each other. At approximately 150 s, the distance between the parafoils gradually converges to a stable value. There are two stable values, one is about 120 m, the other is about 85 m. As can be seen from Fig. 7 above, the expected formation distance of virtual structures is 120 m or 84.9 m. Therefore, the actual formation distance gradually converges to the desired formation distance. From Fig. 15, we can also see that the distance has not been further reduced after formation, in addition, the minimum distance between parafoils is about 10 meters, so there is no collision between parafoils, which ensures the safety for all parafoils. This results show the effectiveness of this method in collision avoidance.

VI. CONCLUSION

In this paper, a formation guidance strategy based on a virtual structure was proposed to solve the formation motion problem for multiple parafoils. The desired trajectory of the virtual structure reference point was first planned based on the multiphase homing method. Next, the virtual structure formation position in the formation coordinate system was transformed into an inertial coordinate system and superimposed on the planning trajectory, and then the reference trajectories of the virtual structure were generated. Finally, the guidance law was designed by using Lyapunov theory, which drives each parafoil to track the corresponding reference point on the virtual structure so that the formation error is gradually reduced and the formation is formed. The simulation results show that the method can make scattered parafoils gather together and follow the desired formation trajectories, and a safe distance between the parafoils is ensured, i.e., the parafoils will not collide with each other. All parafoils eventually upwind land in the vicinity of the target point.

In this paper, the influence of obstacles such as mountains is not considered. Moreover, the control of an inner loop for a parafoil is not considered. In the future, formation

obstacle avoidance in complex environments and the inner loop control will be further studied.

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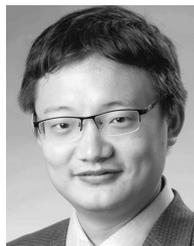
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