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Multi-Objective Cooperative Paths Planning for Multiple Parafoils System Using a Genetic Algorithm

Chen Qi[1,2], Zhao Min[1*], Jin Yanhua[1], Yao Min[1]

Chen Q https://orcid.org/0000-0002-8154-6309
Zhao M https://orcid.org/0000-0002-9602-1935
Jin Y https://orcid.org/0000-0002-5722-6807
Yao M https://orcid.org/0000-0001-5416-9192

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ABSTRACT: In large-scale natural disasters and military supplies, multiple parafoils are more capable of performing actual tasks. The cooperative paths planning for multiple parafoils with different initial positions and headings is an important step in multiple parafoils airdrop, which has to satisfy multiple objectives, namely, parafoils can't collide with each other, parafoils should rendezvous at same target area, most of parafoils need to keep alignment against wind, and planned paths should be in the range of maneuver performance constraints to ensure that every parafoil's path is flyable. Due to more factors need to be considered, it is more difficult to plan paths for multiple parafoils than single parafoil. In this paper an improved genetic algorithm is used to solve the multi-objective cooperative paths planning problem of multiple parafoils system. Parafoils' paths are encoded by real matrix, and the cooperative relationship between parafoils is realized by paths fitness function. The random single point crossover and Gaussian mutation are introduced to accelerate algorithm convergence rate. Finally, a simulation example is given, simulation results show that proposed method can plan feasible paths for all parafoils, meanwhile, it satisfies the requirements of anti-collision, rendezvous to target point, and keep alignment against the wind.

KEYWORDS: Multiple parafoils, Cooperative paths planning, Genetic algorithm, Multi-objective, Anti-collision, Alignment against the wind, Rendezvous.

INTRODUCTION

Parafoil is a pneumatic deceleration device with bilayer structure made of flexible textile material, its speed and heading can be controlled by pulling down the steering line at the trailing edge. When pulling down the steering rope at one trailing edge, the unilateral resistance of the parafoil will increase, which produces yawing moment and changes parafoil's heading, then the turn flight can be achieved. Correspondingly, when pulling down the steering rope at both trailing edges, which changes the overall resistance of the parafoil system and the parafoil's velocity, then the gliding flight can be achieved.

Compared with the traditional round parachute, parafoil has a higher lift-drag ratio, more excellent gliding performance, better stability and maneuverability, and also can be packaged like a traditional round parachute. Meanwhile, parafoil has the advantage of lightweight and small size, which can deliver the soldiers, weapons and military supplies rapidly and accurately to the target area from long-distance, so it is particularly suitable for large-scale disaster reliefs, battlefield supplies, aircraft recycling and other similar tasks.

1.Nanjing University of Aeronautics and Astronautics – College of Automation Engineering – Department of electronic information engineering – Nanjing/Jiangsu – China.
2.Huaiyin Institute of Technology – Faculty of Electronic Information Engineering – Department of electronic information engineering – Huaiyin/Jiangsu – China.
*Correspondence author: xymzhao@126.com

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In recent years, parafoil technology has been developing rapidly; many autonomous controlled parafoil systems developed by many companies and organizations have entered a practical stage, such as autonomous GPS parafoil cargo transport systems from Airborne Systems Company, Onyx Autonomously Guided Parafoil Systems from Atair Aerospace, Sherpa parafoil airdrop system developed by Canada MMIST Company, and so on. Most of the parafoil systems aforementioned have been selected into the JPADS (Joint Precision Airdrop System) project, this project aims to ensure that when US military enters a decentralized and turbulent battlefield without safe and reliable logistics, the high altitude and long distance airdrop parafoil can enhance the US combat effectiveness and maintain its flexible tactical advantages (Benney *et al.* 2009). In addition to companies, NASA also has its own accurate airdrop project called X-38 Program, which was used for the safe landing of Crew Return Vehicle (CRV) of International Space Station; the area of large deployable parafoil utilized in this program is up to 700 m^2, although this project was canceled in 2003, but the X-38 CRV of Space Station that weighs 11 tons has been landed at the target point accurately and safely by a parafoil, and most of the tests were completed and its desired purpose was achieved before this cancellation.

Europe also has its own autonomous parafoil project, for example, the Smart Parafoil Autonomous Delivery System (SPADES) developed by Netherlands Dutch Space Company. The European Union has also funded a project called FASTWing CL (Folding, Adaptive, Steerable Textile Wing Structure for Capital Loads), the area of large-scale guided parafoil developed in FASTWing CL is 300 m^2. Its glide ratio is greater than 5, and the maximum load capacity is 6 tons. This autonomous parafoil system is mainly used for humanitarian relief and aerospace aircraft recycling (Stein *et al.* 2005).

Many institutions in China also engage in the study of parafoil, for example, Li *et al.* (2012) from China Academy of Space Technology designed the fixed-point homing parafoil control system, which has two working modes: automatic homing and manual remote control homing. Qi *et al.* (2015) from Shenyang Institute of Automation, Chinese Academy of Sciences, developed a soft wing unmanned aerial vehicle composed of flexible ram-air parafoil and power device, which has implemented the remote control with the ground station. Nanjing University of Aeronautics and Astronautics Research Group, where the author works, and China Avic Hongguang Airborne Equipment Co. Ltd. jointly developed an airdrop test system for the air flow parameter test of parafoil airdrop system and parafoil control; the designed airdrop test system achieved the desired goal and passed a series of tests in the actual airdrop.

Most of the above-mentioned autonomous parafoil systems are equipped with Airborne Guidance Unit (AGU) as a controller. AGU is generally equipped with parafoil computer, inertial measurement unit, GPS, altimeter, wireless data transfer radio, motor controller, etc. After obtaining the measured parameters, the AGU can issue a control command according to the integrated control information and homing control law, and control the steering rope at both trailing edges through the executive motors. Therefore, the parafoil can realize autonomous navigation flight from the initial release point to the target location based on the pre-set flight path.

In general, from a technical point of view, the single parafoil has the capability of autonomous flight, and the autonomous homing can be achieved according to pre-planned path. A reasonable paths planning before the airdrop is an important guarantee for autonomous parafoil system to perform precision landing. At present, there are a large number of research results concerning single parafoil path planning. Xiong *et al.* (2004a) divided the parafoil path into target close section, energy control section and landing section, based on the simplified model of the parafoil, and proposed a path planning method of segmented homing (Jing *et al.* 2004a). Xiong *et al.* (2005) further compared the parafoil homing path method based on segment planning and optimal control, respectively. Xu and Zhou (2010) proposed a parafoil path planning method based on optimal control , which transformed the path optimization problem of parafoil into the parameter optimization problem; they also used the particle swarm optimization algorithm to obtain the near optimum solution of the parafoil path planning. Zheng *et al.* (2011) used improved adaptive genetic algorithm to optimize various sectional parameters of the homing according to the final landing requirements of the parafoil system. In 2012, the chaos particle swarm optimization algorithm was used by Jiao *et al.* (2012) to optimize the homing path of a single parafoil system. Gao *et al.* (2013) proposed a method of homing fault-tolerant design based on Gauss pseudo-spectral method aimed at the problem of abnormal performance of the controlling motor during the homing flight. Zhang Chao *et al.* (2015) proposed a parafoil path planning method by using the improved A * algorithm, the proposed method enables the parafoil to have a good threat avoiding ability and rapid planning ability. Gao *et al.* (2016) also proposed a multiphase homing trajectory planning scheme which applied auxiliary population-based quantum differential evolution algorithm (AP-QDEA); this algorithm can fulfill the requirement of fixed-points and upwind landing for a parafoil system. Tao *et al.* (2016) presented an optimal homing trajectory planning method for parafoil system, which transforms the problem of the optimal control of trajectory planning into a parameter optimization problem of the control vertices of the B-spline basis function, and then an improved quantum genetic algorithm was used to optimize the objective function. Luo *et al.* (2017) proposed a trajectory optimization method for the parafoil system subjected to intricate constraints, which can realize accurate landing, flare landing against the wind, and global optimal control.

There are other outstanding results about single parafoil path planning. In the earlier days, simple homing such as radial homing and cone-like homing with the blind area were the main parts, later the optimal homing and segmented homing were developed (Pearson *et al.* 1977) Slegers and Yakimenko (2009) transformed the problem of parafoil path planning into two-point boundary value problem based on the dynamic inverse method, thus generating the parafoil reference path in inertial coordinate system. Rademacher *et al.* (2009) improved the Dubins path synthesis method based on parafoil reduction model in 2008, used the optimal control to plan the path of single parafoil, and then generated an optimized feasible path. Fowler and Rogers (2014) transformed the path parameters of parafoil into a series of Bezier curves, and used the Bezier curve and spline function to generate the parafoil path.

Path planning on single parafoil has greatly promoted the progress of parafoil technology. But only one parafoil generally doesn't meet the needs of actual airdrop tasks. For example, in Iraq and Afghanistan wars, the US military dropped 900 tons of materials in 2005, and the number increased year by year, by 2008, it reached 7,500 tons. A further example, during the Wenchuan earthquake in China, a large amount of relief materials were needed to be dropped to the disaster areas, but there was not enough airdrop capacity to meet the requirements of earthquake victims. It is apparently that only one parafoil is not enough, there must be multiple parafoils to provide a large amount of supplies.

Multiple parafoils airdrop at the same time in the same airspace has problems don't usually encountered by single parafoil. First, the landing of parafoil must be accurate; otherwise the supplies may be landed at enemy area or an area hard to reach. Secondly, the distribute scope of the parafoils should be small, the parafoils that dropped from different locations should be able to fly to the same target points gradually, otherwise the landing distribution could be too large, so supplies are hard to rendezvous, it is common knowledge that the longer it takes to rendezvous, the lower the possibility of survival in wartime. Thirdly, it is necessary to ensure the safety of all parafoils, the distance between parafoils should not be too small during the process of landing, and otherwise the parafoils could collide with each other. Finally, in order to reduce landing speed and landing impact of parafoil, parafoils should alignment against the wind; alignment against the wind is a special requirement for airdrop, which is not necessary in the common multi-UAV path planning. Generally speaking, we should consider above issues and plan paths holistically according to the actual situation.

In summary, the current parafoil already has the ability to fly autonomously, so it is possible to plan feasible paths for multiple parafoils. The studies about single parafoil path planning have achieved remarkable results in terms of both theory and practice; however, multiple parafoils are more meaningful in actual airdrop tasks. Hence, how to plan feasible paths for all parafoils has become an urgent problem to be solved. Compared with single parafoil path planning, multiple parafoils paths planning is a more difficult multi-objective optimization problem with multiple constraints, strong coupling and non-linearity, so it has certain theoretical value. In view of the above problems, this paper explores the paths planning method, hoping to provide theoretical reference for the development of parafoil technology.

PROBLEM DESCRIPTION OF MULTIPLE PARAFOILS SYSTEM PATHS PLANNING

PARTICLE MODEL OF PARAFOIL SYSTEM

Physical model of autonomous parafoil is associated with the dynamic equation and kinematic equation, as well as the aerodynamic resistance, lift and apparent quality, which is a highly complex nonlinear system. The commonly used models include 4 DOF (degrees of freedom), 6 DOF, 8 DOF, and 9 DOF model, the more complex the model, the more state parameters are available, but the higher the computational complexity. Under the circumstance that the relative motion of parafoil load relative to canopy does not need to be considered, the motion equation can be simplified, and the complex model with high degree of freedom can be replaced by parafoil particle model in order to simplify the problem scale. In recent years, researchers such as Fowler and Rogers (2014), Cleminson (2013), Luders *et al.* (2013), Xiong *et al.* (2004b), Gao *et al.* (2013), Zhang and Zhu (2011), Jiao *et al.* (2012), Xie Ya-rong *et al.* (2010), Zhang *et al.* (2013) and Zheng *et al.* (2011) have studied the particle model of parafoil system and obtained the following conclusions and assumptions:

- The effect of double-sided pull-down on the gliding performance of parafoil system is small, and the changes of gliding ratio are small along with the double-side deviation, so the gliding ratio can be regarded as a constant. Therefore, while analyzing and considering the parafoil control, the turning control by pulling down one trailing edge should be focused, as the bilateral pull-down is mainly used for the flared landing during final landing;
- Under the steady state, the changes of parafoil vertical speed after parafoil full expansion is not large, so it can be regarded as constant. Besides, as the gliding ratio is constant, so the horizontal speed also can be regarded as the constant;
- Considering the wind field as a horizontal wind field and the wind field can be predicted;
- The effect of the wind can only cause the position offset, regardless of the impact of the wind on the parafoil gesture;
- The response of parafoil is not delayed to control input.

Under above assumptions, and taking horizontal wind direction as the X-axis direction, we can take the fixed wind coordinate frame as the system coordinate frame. The influence of wind is transformed into the offset of initial point position (Xiong *et al.* 2004a), and the motion model of N parafoil systems is as follows:

$$\begin{cases} \dot{x}_i = V_s \cos\psi_i \\ \dot{y}_i = V_s \sin\psi_i \\ \dot{z}_i = V_z \\ \dot{\psi}_i = u_i \end{cases} \quad i = 1,\dots,N \tag{1}$$

where N is the total number of airdrop parafoils, the state of ith parafoil is $X_i = [x_i, y_i, z_i, \psi_i]^T$, and (x_i, y_i, z_i) are position coordinates of ith parafoil in the wind fixed coordinate system. V_s is horizontal speed of parafoil, V_z is vertical speed of parafoil, ψ_i is turning angle, $\dot{\psi}_i$ is turning angle speed, u_i is control input, which has a corresponding relationship with the single-sided pull-down amount. As can be seen from Eq. 1, the model is a nonlinear model.

AIRDROP FEASIBLE REGION OF PARAFOIL

The ratio between horizontal glide distance and the release height of parafoil is the glide ratio. From above assumptions and conclusions, it can be seen that glide ratio of parafoil system can be regarded as a constant, when the airdrop height is certain, then the horizontal gliding distance is limited. The parafoil system is not likely to land at the intended target point at some initial position and state, that means that if horizontal distance of airdrop release point is too far from target point, the ratio between horizontal distance and release altitude will be greater than glide ratio, indicating that parafoil dropped in this region will land on

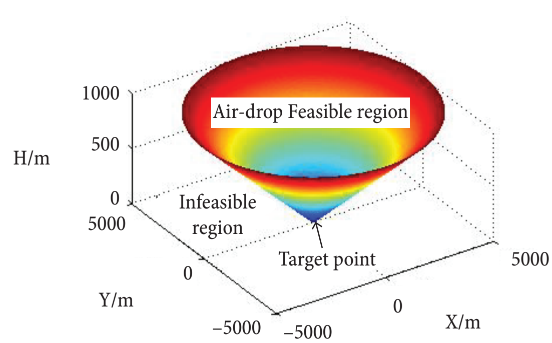

Figure 1. Airdrop feasible region of parafoil system.

the ground before reaching the target point. Such airdrop region is known as infeasible region, as shown in Fig. 1, the red circular conical surface is the critical surface, the exterior domain of the surface is infeasible region; parafoils dropped from this region are destined not to land at the target point, what the parafoil can do only is transfer the gliding direction to the target point, making the landing point close to the target point as much as possible.

The region within the red circular conical surface is called as airdrop feasible region. Parafoils dropped in this region have sufficient altitude to complete the maneuver. Therefore, the homing path of each parafoil to the target point can be planned in the feasible region by combining initial state of each parafoil system with the parafoil characteristics. The multi-objective paths planning of multiple parafoils system mentioned in this paper is implemented in this region.

DEFINITION ABOUT MULTIPLE PARAFOILS AIRDROP PLANNING PATHS

As mentioned above, it is necessary to consider avoiding collision, rendezvous and upwind landing constraint in multiple parafoils paths planning. Therefore, the multiple parafoils planning paths are defined as flight trajectories planned for multiple parafoils from the initial points to target point in a certain planning space (that is, within the airdrop feasible region) under certain constraints combined with certain target functions. The planned paths are not necessarily optimal for each parafoil, but it is optimal or suboptimal for the entire parafoil formation. The multiple parafoils airdrop schematic diagram is shown in Fig. 2.

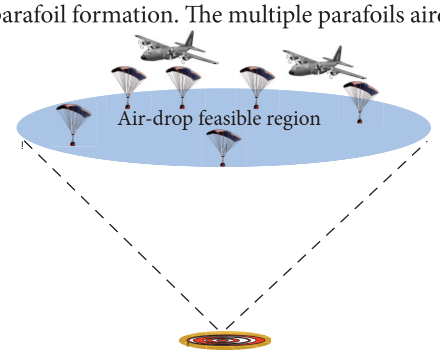

Figure 2. Multiple parafoils airdrop diagram.

MULTIPLE PARAFOILS PATHS PLANNING BASED ON GENETIC ALGORITHM

Within the airdrop feasible region, there are many possible parafoil paths from multiple initial release points to the target point. It is a tough task to find out which paths satisfy the constraint conditions, but the genetic algorithm can find the most feasible ones. Genetic algorithm is an iterative adaptive probabilistic search algorithm; it emulates the evolution rule of "Survival of the fittest in natural selection" in the biological world (Cabreira *et al.* 2013). Firstly, the genetic chromosomes are obtained by coding the parafoil paths, and then using the iterative method to select, crossover and mutate the chromosomes. These genetic operations exchange the information of chromosomes in the population, and finally generate the paths that meet the requirements of multiple parafoils. Genetic algorithm is not demanding on huge storage space, and it usually uses objective function to conduct self-adaptive search on all solutions under the guidance of the probability, so it is possible to search for the optimal or approximate optimum solution among all solutions without falling into the local optimal solution. Therefore, how to encode the paths, design the fitness function, and then select the appropriate genetic operation are key problems to be solved in paths planning. If the design is reasonable, it can avoid the phenomenon of too many iterative steps, slow convergence rate and the falling of local extremum.

MULTI-OBJECTIVE CONSTRAINTS CONDITIONS

Boundary Conditions

For a given multiple parafoils paths planning task, the initial time is set to be t_0. The state of the parafoil is known at this moment, that is to say, the release position and heading angle of each parafoil are known, which are $X_0 = [X_{i0}, i = 1, \ldots N]^T$, and in the case that the planning is feasible, the parafoil will reach the landing target point (x_f, y_f, z_f) at the final time of t_f, and most of the parafoils will meet the conditions of the upwind alignment.

Maneuverability Constraints

The parafoils are mainly controlled by the steering rope on the winch driven by the motor. The pull-down strokes of left and right steering ropes are limited, and when the parafoil rope is pulled down to the maximum stable single-sided amount, the corresponding turn radius is the minimum while the turning angle is the maximum (Xiong *et al.* 2005). Parafoil's turning angle must be less than this maximum value, otherwise the maneuverability constraints of parafoil will not be met, and the generated path will not be feasible. The angle constraint of the parafoil is (Eq. 2):

$$\left|\psi_i\right| \leq \psi_{\max} \tag{2}$$

The corresponding rate of change is u_i, i.e., the control constraint is (Xiong et al. 2004b) (Eq. 3):

$$\left|u_i\right| \leq u_{\max} \tag{3}$$

This maximum control value corresponds to the minimum turning radius.

Rendezvous Constraints

Generally speaking, airdropped supplies and materials by multiple parafoils are needed to land at the same target point in the modern combat environment or earthquake relief. However, after the airdrop, the initial position and direction angle may be different due to a variety of factors, resulting in the majority of parafoils being scattered in different places, which has a great impact on the rapid assembly of supplies. In this paper, the method similar to potential field is adopted to achieve rendezvous. The target point is set to an attract point, each parafoil is attracted by the target point, hence the distance to the target points tends to be 0, i.e. (Eq. 4):

$$\left\| x_i\text{-}x_f, y_i\text{-}y_f, z_i\text{-}z_f \right\| \rightarrow 0, i=1,\ldots,N \tag{4}$$

where the landing target point (x_f, y_f, z_f) is set to be (0, 0, 0) in this paper.

Anti-Collision Constraints

There are two major categories of solutions that can solve the problem of mutual-collision between multiple parafoils. The first category is the space solution: each parafoil has its own flight range and the ranges aren't overlapped, which can prevent the mutual-collision between parafoils, but a lot of feasible spaces will be wasted, and it is also possible to lead to planning failure. The second solution has no space constraints, but it needs to ensure that different parafoils can't appear at the same position at the same time. This paper adopts the second solution, in other words, a certain safety distance has to be kept among parafoils at any time.

$$\left\| x_i\text{-}x_j, y_i\text{-}y_j, z_i\text{-}z_j \right\| \geq L_{\min}, \forall i \neq j \tag{5}$$

where L_{min} is the minimum safe distance to avoid collision, Eq. 5 means the distance between *i*th parafoil and *j*th parafoil should be larger than the safe distance L_{min}.

Upwind Alignment Constraints

The parafoil is required to align against the wind as far as possible before reaching the target point, i.e. the flight direction of parafoil should be opposite to the wind direction, in order to meet the requirement of flared landing. When the parafoil approaches to the ground, if the steering rope at both trailing edges is pulled down rapidly, the parafoil will aerodynamic stalls, as a result, the parafoil's forward speed and vertical speed will be rapidly reduced (close to zero), it is called flared landing. This operation is named after imitating the bird's landing. It should be noted that parafoil stall is not an option during the process of gliding, but only in the landing stage. Assuming that the wind direction angle near the target point is ψ_w, then the direction angle at the time of landing should meet (Eq. 6) (Chen and Zhang 2013):

$$\psi_i(t_f) = (2k+1)\pi + \psi_w, k \in Z, i = 1, \ldots, N \tag{6}$$

where $\psi_i(t_f)$ is the turning angle of the ith parafoil during landing. In the aforementioned paper, the wind fixed coordinate frame has been taken, the wind direction has been assumed to be positive X-axis, so ψ_w is set to zero.

MULTI-OBJECTIVE FUNCTION

Different objective functions can be needed according to different airdrop tasks. If all parafoils are required to be rendezvoused quickly when landing, then the paths planning objective of the multiple parafoils system is designed to minimize the landing error, which can be described by the following objective function (Eq. 7):

$$J_1 = \min \sum_{i=1}^{N} \sqrt{(x_i(t_f) - x_f)^2 + (y_i(t_f) - y_f)^2} \tag{7}$$

If it is required that the parafoils can't collide but draw close with each other during the process of airdrop, then the following objective function can be used as shown in Eq. 8. On one hand, the parafoils must gradually draw closer to each other; on the other hand, when the parafoil distance tends to a safe distance, no further closer will be drawn, in order to avoid the collision.

$$J_2 = \min(\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} - L_{\min}), \forall i \neq j \tag{8}$$

If it is required that all parafoils should realize alignment against the wind as far as possible, the following objective function can be used (Eq. 9):

$$J_3 = \min \sum_{i=1}^{N} (\psi_i(t_f) - \psi_f) = \min \sum_{i=1}^{N} (\psi_i(t_f) - (2k+1)\pi), k \in Z \tag{9}$$

In the specific paths planning, we can choose one of the objective functions or weight the objective functions, the total objective function obtained is as follows (Eq. 10):

$$J = \alpha_1 J_1 + \alpha_2 J_2 + \alpha_3 J_3 \tag{10}$$

where α_1, α_2, α_3 indicate the weighted factor of the corresponding objective, and the appropriate weight can be selected according to the specific task requirements. In the paths planning, the above function is used as a fitness function.

GENETIC ALGORITHM IMPLEMENTATION AND SIMULATION EXPERIMENT

PATHS MATRIX WITH REAL NUMBER CODING

When the genetic algorithm is used to solve the problem of paths planning, it is necessary to transform the paths information into the available chromosome in the genetic algorithm, that is, to encode the paths. Assuming that a total of N parafoils has been dropped, then each parafoil has its own path, and each parafoil path has a number of path nodes (assumed to be M). Each path is consisted by these nodes and connection lines between them, so that each chromosome can be represented by a $N \times M$ matrix (Eq. 11):

$$A=\begin{bmatrix} \psi_{11} & \psi_{12} & \cdots & \psi_{1M} \\ \psi_{21} & \psi_{22} & \cdots & \psi_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ \psi_{N1} & \psi_{N2} & \cdots & \psi_{NM} \end{bmatrix} \tag{11}$$

where each element of the matrix is a genetic locus, which is encoded by real numbers, of which, the i row and j column generic locus ψ_{ij} corresponds to the turning angle of the jth path point of the ith parafoil. Therefore, the paths planning problem of the multiple parafoils is transformed into the optimal chromosome problem to meet the constraint conditions. Matrix coding reduces the complexity by encoding the chromosome as a real number matrix rather than encoding it as a long binary string. It also can reduce the likelihood of invalid crossover and ensure the integrity of the offspring genes, which is helpful to achieve optimal solution with high precision in a short time. Since the horizontal velocity and the descending velocity of the parafoil are set to be constant in the gliding state, and the initial position (x_{i0}, y_{i0}, z_{i0}) and initial turning direction angle ψ_{i0} of the parafoil are known, then the position of parafoil at each path node can be obtained through iterative calculation. That is to say, the position (x_i, y_i, z_i) can be calculated iteratively according to Eq. 1. The turning direction angle ψ_{ij} is a constrained amount, its value can be positive, negative or zero, which corresponds the left turn, right turn or straight glide of the parafoil. Therefore, the paths are represented by the chromosome, and the merits of paths can be evaluated by calculating the fitness value of all chromosomes. The smaller the fitness value is, the more the paths satisfy the planning requirement.

POPULATION INITIALIZATION

It is necessary to carry out the initialization of the paths population before algorithm starts, it refers to generate a series of initial path individuals, i.e., generate the navigation point coordinates in the paths. The number of individuals selected in this paper is N_p, it is an even number to facilitate subsequent cross operations.

GENETIC OPERATIONS

Selection

The purpose of selection is to select good individuals from the parent group, so that they have more opportunities to be parent and breed offspring as the next generation. Selection operation reflects Darwinian's survival of the fittest principle. In this paper, the selection method is as follows: first, the crossed and mutated population and parent population are put into the breeding pool together, and then the fitness value of all the individuals in the breeding pool is calculated. The individuals with small fitness values are better and have higher probability to be reserved for the next generation. This approach can ensure that the optimal individual has a greater probability of entering the next generation while avoiding prematureness, in other words, the genetic deletions can be avoided, and the global convergence and computational efficiency can be improved.

Crossover

Crossover is the most important genetic operation of genetic algorithm, as new generation of individuals can be obtained through the crossover; crossover operation combines with the characteristics of parent individuals. The crossover embodies the idea of information exchange and determines the global search performance of the algorithm. Since the population size N_p is even, so the crossover can be done by means of two pairs of random pairings. Here's how it works: first, a random pairing table is generated, and two individuals selected according to the pairing table will be crossed in the population. The two random selected individuals are called A^t and B^t in this paper, where each individual is a matrix with N row and M column. In the following, a random number that is smaller than M is produced and set to be P_0. In this way, the new offspring A^{t+1} and B^{t+1} can be obtained from the following formulas (Eqs. 12 and 13):

$$A^{t+1}=\left[A^{t}(1:P_0),B^{t}(P_0+1:M)\right] \tag{12}$$

$$B^{t+1}=\left[B^{t}(1:P_0),A^{t}(P_0+1:M)\right] \tag{13}$$

In other words, the new offspring is derived from the front P_0 column and the post (M – P_0) column of another parent generation by crossover.

Mutation

The main purpose of mutation is to maintain the diversity of the population. In this paper, Gaussian mutation is used to produce new offspring. Gaussian mutation operation refers to update the genetic locus by the random number that obeys Gaussian distribution (i.e., normal distribution) with mean value of μ, and variance of σ^2. A random number is generated first, and if the random number is less than the mutation probability P_m, the genetic locus will be updated with mutation operation. Assumed that the genetic locus of the chromosomes at the i row and j column is ψ^t_{ij} before the mutation, but after mutation operation, a new genetic locus ψ^{t+1}_{ij} is obtained as follows (Eq. 14):

$$\psi_{ij}^{t+1}=\psi_{ij}^{t}+\nu \tag{14}$$

where ν is a random variable, ν a $N(0, \sigma)$, that is, ν complies with Gaussian distribution, and (Eq. 15):

$$\sigma=(\psi_{\max}-\psi_{\min})/\gamma \tag{15}$$

where γ is the variation amplitude adjustment factor, with the value between 3 and 50, and 50 is taken in this paper, ψ_{max} is the maximum turning angle, $\psi_{max} = -\psi_{min}$. If Gaussian mutation is adopted, the worse the fitness, the more likely the mutation occurs. Therefore, while increasing the diversity of the population, it also maintains the high fitness of the population and accelerates the convergence of the algorithm.

In order to determine whether it is necessary to accept the mutation individual, it requires recalculate the fitness value of individuals before and after the mutation. If the mutation individual's fitness value gets smaller, and the probability of acceptance is higher than the acceptance possibility P_a of mutation deterioration, the mutation shall be accepted, and mutation individuals shall be retained; otherwise, the mutation shall be abandoned.

ALGORITHM TERMINATION CRITERIA

Generally, it is difficult for genetic algorithm to find the global optimal solution, but a satisfactory solution meeting the requirements is possible to be found. We can set the maximum evolutionary iterations number as the upper limit, and terminate the algorithm when the evolutionary iterations number reaches to the upper limit. In addition, if the next generation individual's fitness remains basically the same relative to the previous generation, that is to say, the fitness changes is smaller than a certain set value, the algorithm will be terminated to reduce the calculation time. The two methods can be used together. During the evolution, once the solution has no significant reduction, the algorithm will be terminated; otherwise, it will be continued until reach the upper limit of evolutionary iterations number.

ALGORITHM DESCRIPTION

Figure 3 shows the genetic algorithm flow chart for multiple parafoils paths planning. Assuming that the airdrop parafoils number is N, then the cooperative paths are composed of N paths. Each parafoil's path consists of a series of nodes; they are connected by straight line, where the first node and the last node respectively as the starting point and the target point.

The algorithm steps are as follows:

- During initialization, the chromosome is randomly coded as an $N * M$ dimension real matrix firstly, then the population includes N chromosomes is generated randomly according to the planning tasks. Each chromosome represents a feasible paths set.
- The chromosome is crossover with foregoing evolutionary mechanism, and generates the new offspring.
- The child and the parent generation are put into the breeding pool together. The paths are regenerated by the chromosomes. The next job is to calculate the paths' fitness values by multi-objective function, which realizes the objectives of collision detection and adjustment, upwind alignment, and the fixed-point drop. Then the worst individuals in breeding pool will be deleted with a certain probability, make the population restore to its original size.
- The genes of the chromosomes are altered by Gauss mutation. If the mutated chromosome is better than the original one then keep the mutation, otherwise abandon it.
- The algorithm judges whether the termination condition is met, and if it is met, the evolutionary process will be terminated, otherwise a new iteration is restarted.
- The optimal individual from the population is selected, and the multiple paths that satisfy the requirement of multi-objective are generated simultaneously, work is done.

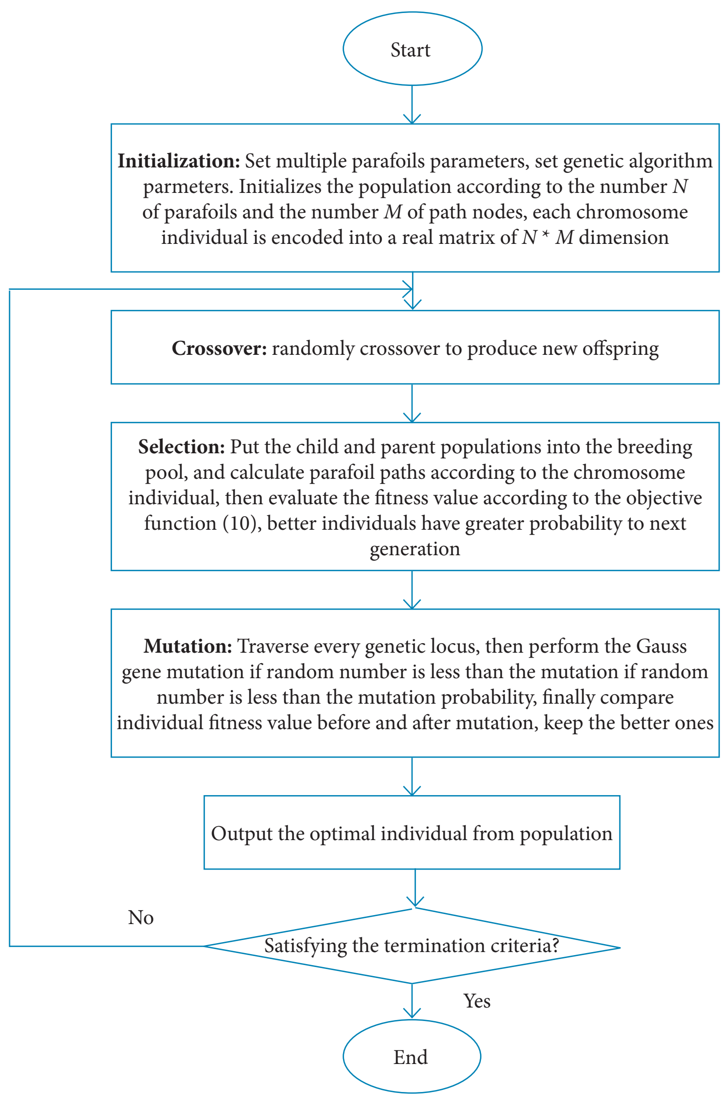

Figure 3. The genetic algorithm flow chart.

SIMULATION EXPERIMENT

In this paper, the algorithm simulation is carried out in MATLAB environment. Six parafoils are dropped simultaneously from the height of 2000 m and are demanded to land at the same target point (0, 0, 0). The initial drop position and the initial heading simulation parameter settings are shown in Table 1, and the other paths planning parameters of are shown in Table 2.

Table 1. Parafoils initial states.

Parafoil no.	Initial coordinate	Initial heading angle
1	(1500, 600, 2000)	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°

Table 2. Paths planning simulation parameter settings.

Parameter	Value	Parameter	Value
Parafoil glide ratio	3	Population size N_p	400
Horizontal speed V_s	15 m/s	Mutation probability P_m	0.8
Vertical speed V_z	3 m/s	Mutation acceptance probability P_a	0.25
Landing target points	(0, 0, 0)	Mutation amplitude adjustment factor γ	50
Minimum turning radius	200 m	Weight factor α_1	20
Parafoil maximum turning angle ψ_{ij}	17.4576°	Weight factor α_2	1
Parafoils number N	6	Weight factor α_3	1
Minimum safe distance L_{min}	8 m	Maximum iterations number K	200
Upwind alignment angle $\psi_i(t_f)$	180°	Number of path nodes	50

The minimum anti-collision safety spacing L_{min} ensures that planned parafoils paths do not overlap in the same spatial position at the same time. The maximum value of parafoil turning angle ψ_{ij} and the minimum turning radius assures that the planned paths are flyable for each parafoil. The upwind alignment turning direction angle $\psi_i(t_f)$ allows the majority of parafoils to be aligned against the wind when landing at the target point.

The results of multiple parafoils paths planning using GA are shown in Figs. 4 to 8. In the simulation, the weight factors α_1, α_2, and α_3 are set to 20, 1, and 1 respectively.

The initial position of the parafoil 1 to the parafoil 6 was marked with Para.1 – Para.6 in Fig. 4, which shows that the initial position and direction angle of each parafoil are different. It can be seen from the simulation results that all the 6 parafoils from different locations with different direction angles landed near the same expected landing target point (0, 0, 0). It is also known that a safe spacing between them is maintained above 8 m and the collision is avoided. In addition, most of the parafoils achieved the alignment against the wind, almost all parafoils have an final landing angle of 180°, as shown in the partial magnification in Fig. 4. The paths planned by the genetic algorithm also satisfy the requirements of the parafoil maneuvering performance; all parafoils's turning angle is less than 17.4576°. Therefore, the multiple objectives requirement of multiple parafoils paths planning is realized.

Figure 6 shows the landing scatter of all parafoils. As we can see, all of the parafoils are basically distributed in a circle with a center at the impact point and a radius of 100 m.

Figure 7 shows the convergence curve of the algorithm. It can be seen that the convergence rate of the algorithm is relatively fast, and it is close to convergence after the 43rd iteration.

The choice of α_1, α_2, α_3 values has a great impact on the planned outcome; different weight factor will lead to different planning results. For example, if we need to further reduce the landing error, we can increase the weighting factor α_1, as a comparison with the case ($\alpha_1 = 20$, $\alpha_2 = 1$, $\alpha_3 = 1$), we set α_1, α_2 and α_3 to be 40, 1, and 1, respectively. The corresponding results ar

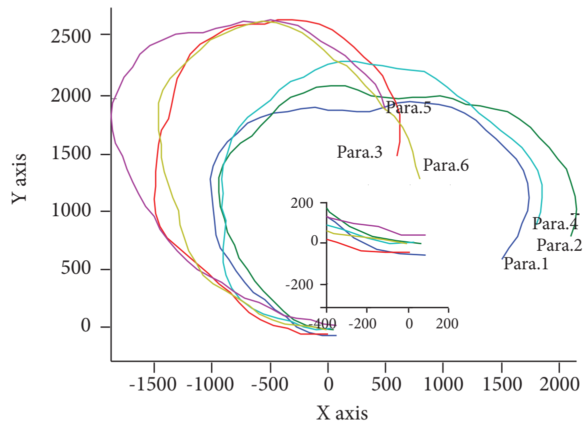

Figure 4. Projection of the parafoils planning paths in the horizontal plane ($\alpha_1 = 20$, $\alpha_2 = 1$, $\alpha_3 = 1$).

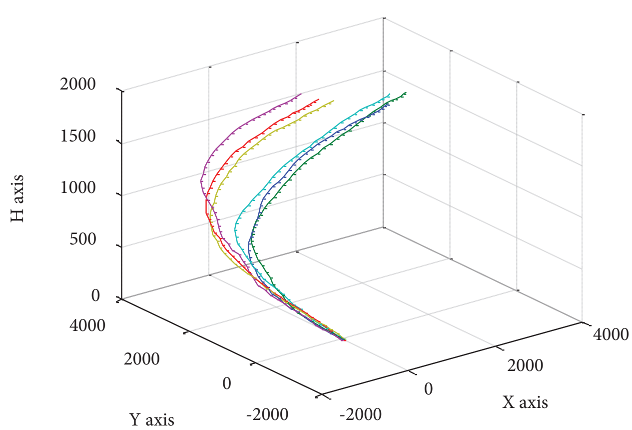

Figure 5. Parafoils planning paths in 3D space ($\alpha_1 = 20$, $\alpha_2 = 1$, $\alpha_3 = 1$).

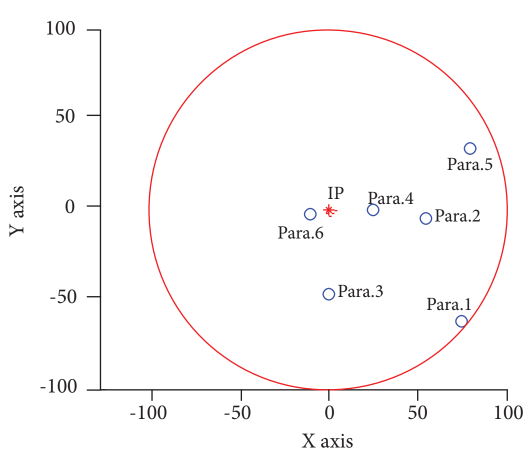

Figure 6. Parafoils landing scatter diagram ($\alpha_1 = 20$, $\alpha_2 = 1$, $\alpha_3 = 1$).

shown in Figs. 8 to 11. Comparing Figs. 6 and 10, we can see the landing error is indeed reduced, but we also can find that the effect of alignment against the wind became worse, comparing Figs. 4 and 8, we can see that landing angle of part parafoils is less than 180°. Therefore, it is necessary to consider task demand comprehensively and achieve balance of each objective in the airdrop mission.

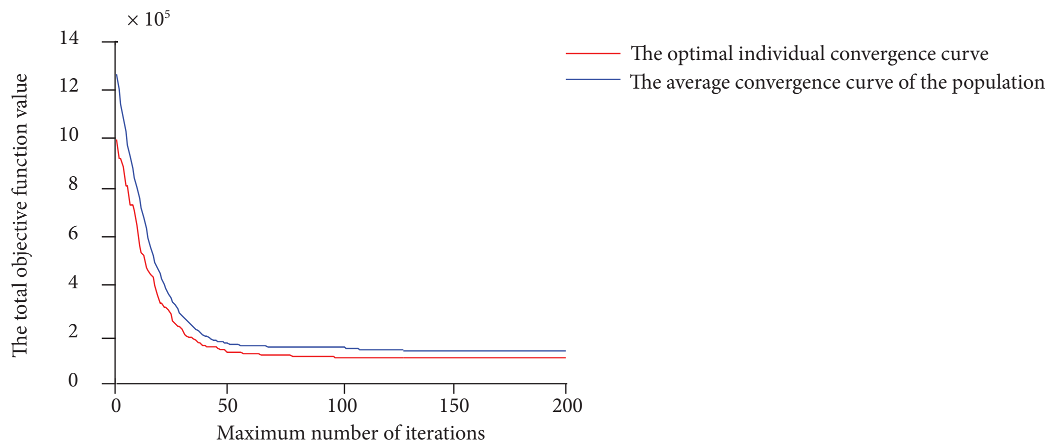

Figure 7. Convergence curve of genetic algorithm (α_1 = 20, α_2 = 1, α_3 = 1).

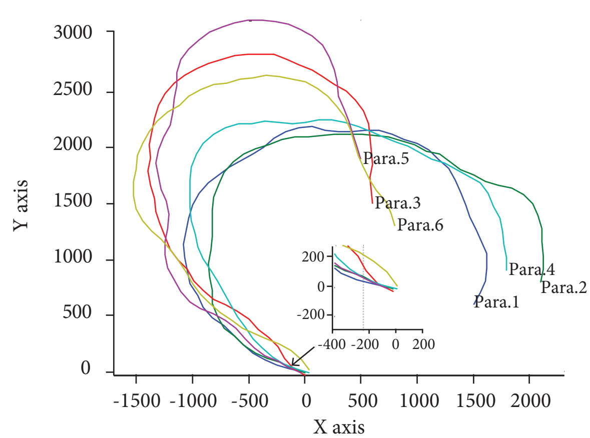

Figure 8. Projection of the parafoils planning paths in the horizontal plane (α_1 = 40, α_2 = 1, α_3 = 1).

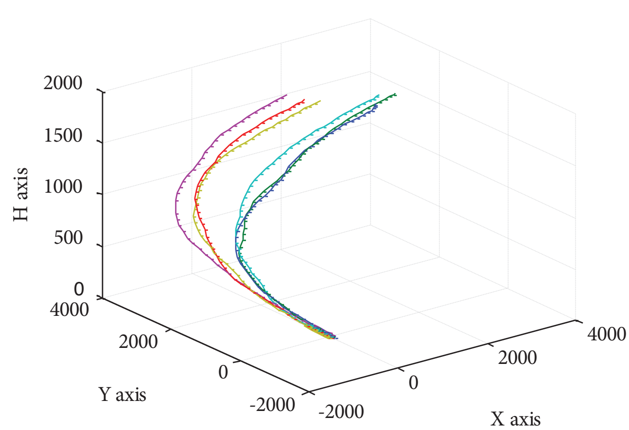

Figure 9. Parafoils planning paths in 3D space (α_1 = 40, α_2 = 1, α_3 = 1).

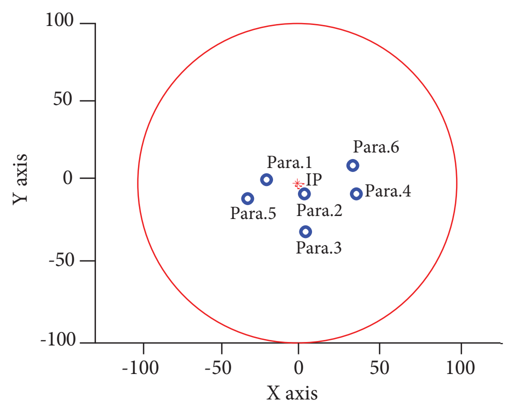

Figure 10. Parafoils landing scatter diagram (α_1 = 40, α_2 = 1, α_3 = 1).

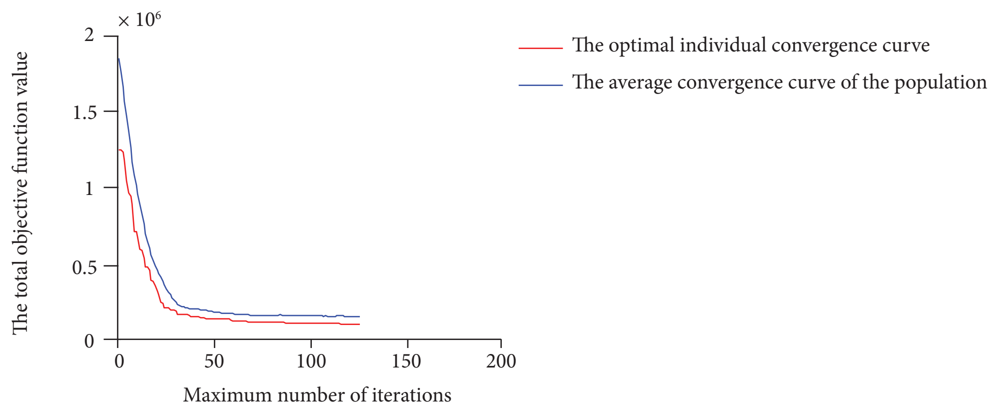

Figure 11. Convergence curve of genetic algorithm (α_1 = 40, α_2 = 1, α_3 = 1).

CONCLUSION

Paths planning of parafoils are the key part of the parafoil's autonomous homing. The traditional path planning mainly focuses on single parafoil, the main optimization objective is to minimize the landing error, and does not need to take the cooperative of multiple parafoils into consideration. Of course, there is no cooperative planning problem with single parafoil, cooperative planning problem exists only when there are multiple parafoils.

In this paper, the problem of multiple parafoils cooperative paths planning is studied. The main purpose of cooperative paths planning is to avoid parafoils collide with each other to ensure the safe flight, and keep the alignment against the wind during landing to achieve the flared landing; meanwhile, all the paths need to satisfy the dynamic characteristics of the parafoil to ensure that the path is flyable. In this paper, the genetic algorithm is used to solve he planning problem of multiple parafoils, and simulation results show that the expected effect is achieved. The algorithm is flexible, and even if the model is nonlinear, it also can obtain the results quickly.

AUTHOR'S CONTRIBUTION

Conceptualization, Chen Q; Methodology, Chen Q and Zhao M; Investigation, Chen Q, Zhao M, Jin Y and Yao M; Writing, Chen Q, Zhao M, Jin Y and Yao M; Supervision, Zhao M.

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REFERENCES

Benney R, Henry M, Lafond K, Meloni A, Patel S (2009) DoD new JPADS programs and NATO activities. Presented at: 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar; Seattle, USA. https://doi.org/10.2514/6.2009-2952

Cabreira TM, Aguiar MS, Dimuro GP (2013) An extended evolutionary learning approach for multiple Robot path planning in a multi-agent environment. Presented at: 2013 IEEE Congress on Evolutionary Computation; Cancun, Mexico. https://doi.org/10.1109/CEC.2013.6557982

Chen Z, Zhang H (2013) Research on the Optimization of Flare Maneuver Control of the Powered Parachute Based on CFD. Measurement & Control Technology 32(2):51-55.

Cleminson JR (2013) Path planning for guided parafoils: an alternative dynamic programming formulation. Presented at: AIAA Aerodynamic Decelerator Systems Conference; Daytona Beach, USA. https://doi.org/10.2514/6.2013-1346

Fowler L, Rogers J (2014) Bézier curve path planning for parafoil terminal guidance. Journal of Aerospace Information Systems 11(5):300-315. https://doi.org/10.2514/1.I010124

Gao H, Tao J, Sun Q, Chen ZQ (2016) Design and optimization in multiphase homing trajectory of parafoil system. Journal of Central South University 23(6):1416-1426. https://doi.org/10.1007/s11771-016-3194-x

Gao H, Zhang L, Sun Q, Sun MW, Chen ZQ, Kang XF (2013) Fault-tolerance design of homing trajectory for parafoil system based on pseudo-spectral method. Control Theory & Applications 30(6):702-708.

Jiao L, Sun Q, Kang X (2012) Route planning for parafoil system based on chaotic particle swarm optimization. Complex Systems and Complexity Science 9(1):47-54.

Li C, Lu Z-H, Huang W, Schen C (2012) Guidance navigation and control system for precision fix-point homing parafoil. Journal of Central South University: Science and Technology 43(4):1331-1335.

Luders B, Sugel I, How JP (2013) Robust trajectory planning for autonomous parafoils under wind uncertainty. Presented at: AIAA Infotech Aerospace Conference; Boston, USA. https://doi.org/10.2514/6.2013-4584

Luo S, Sun Q, Tan P, Tao J, He Y, Luo H (2017) Trajectory planning of parafoil system with intricate constraints based on Gauss pseudo-spectral method. Acta Aeronautica et Astronautica Sinica 38(3):220-230. https://doi.org/10.7527/S1000-6893.2016.0254

Pearson AE, Wei KC, Koopersmith RM (1977) Terminal control of a gliding parachute in a nonuniform wind. AIAA Journal 15(7):916-922. https://doi.org/10.2514/3.7387

Qi J, Liu J, Shang H, Jang L, Mei S, Han J (2015) Autonomous flight control and simulation study of independent developed soft-wing UAV. Journal of System Simulation 27(12):2988-2997. https://doi.org/10.16182/j.cnki.joss.2015.12.016

Rademacher BJ, Lu P, Strahan AL, Cerimene CJ (2009) In-flight trajectory planning and guidance for autonomous parafoils. Journal of Guidance Control and Dynamics 32(6):1697-1712. https://doi.org/10.2514/1.44862

Slegers NJ, Yakimenko OA (2009) Optimal control for terminal guidance of autonomous parafoils. Presented at: 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar; Seattle, USA. https://doi.org/10.2514/6.2009-2958

Stein JM, Madsen CM, Strahan AL (2005) An overview of the guided parafoil system derived from X-38 experience. Presented at: 18th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar; Munich, Germany. https://doi.org/10.2514/6.2005-1652

Tao J, Sun Q, Zhu E, Chen Z, He Y (2016) Homing trajectory planning of parafoil system based on quantum genetic algorithm. Journal of Harbin Engineering University 37(9):1261-1268. https://doi.org/10.11990/jheu.201507004

Xie Y, Wu QX, Jiang CS, Zheng C (2010) Application of particle swarm optimization algorithm in route planning for parafoil airdrop system. Aero Weaponry 5:7-10+18.

Xiong J, Qin Z, Cheng W (2004a) Optimal design in multiphase trajectory of parafoil system. Space Craft Recovery & Remote Sensing 25(3):11-16.

Xiong J, Qin Z, Cheng W (2005) Design of autonomous homing trajectory for parafoil delivery system. Chinese Space Science and Technology (6):51-59.

Xiong J, Qin Z, Wen H (2004b) Optimal control of parafoil system homing. Aerospace Control 22(6):32-36.

Xu J, Zhou D-Y (2010) A path planning algorithm based on optimal control. Fire Control & Command Control 35(10):59-61.

Zhang C, Liu S-D, Liu J, Xia J (2015) Research on modified A* algorithm based path planning for parafoil system. Computer Simulation 32(1):60-63+131.

Zhang L, Gao H, Chen Z, Sun Q, Zhang X (2013) Multi-objective global optimal parafoil homing trajectory optimization via Gauss pseudospectral method. Nonlinear Dynamics 72(1-2):1-8. https://doi.org/10.1007/s11071-012-0586-9

Zhang X, Zhu E (2011) Design and simulation in the multiphase homing of parafoil system based on energy confinement. Aerospace Control 29(5):43-47.

Zheng C, Wu Q, Jiang C, Xie Y (2011) Optimization in multiphase homing trajectory of parafoil system based on IAGA. Electronics Optics & Control 18(02):69-72.