

## Article

# Path Planning for Autonomous Landing of Helicopter on the Aircraft Carrier

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Received: 23 August 2018; Accepted: 26 September 2018; Published: 27 September 2018



**Abstract:** Helicopters are introduced on the aircraft carrier to perform the tasks which are beyond the capability of fixed-wing aircraft. Unlike fixed-wing aircraft, the landing path of helicopters is not regulated and can be determined autonomously, and the path planning problem for autonomous landing of helicopters on the carrier is studied in this paper. To solve the problem, the returning flight is divided into two phases, that is, approaching the carrier and landing on the flight deck. The feature of each phase is depicted, and the conceptual model is built on this basis to provide a general frame and idea of solving the problem. In the established mathematical model, the path planning problem is formulated into an optimization problem, and the constraints are classified by the characteristics of the helicopter and the task requirements. The goal is to reduce the terminal position error and the impact between the helicopter and the flight deck. To obtain a reasonable landing path, a multiphase path planning algorithm with the pigeon inspired optimization (MPPIO) algorithm is proposed to adapt to the changing environment. Three experiments under different situations, that is, static carrier, only horizontal motion of carrier considered, and 3D motion of carrier considered, are conducted. The results demonstrate that the helicopters can all reach the ideal landing point with the reasonable path in different situations. The small terminal error and relatively vertical motion between the helicopter and the carrier ensure a precise and safe landing.

**Keywords:** helicopter; aircraft carrier; landing; path planning; pigeon inspired optimization

## 1. Introduction

Landing on the flight deck of a carrier is one of the most dangerous tasks for fixed-wing aircraft [1]. Only 70% of aircraft can finish the landing task successfully for one time, and the percentage is even lower at night [2]. When fixed-wing aircraft land on the flight deck, the landing path is regulated. The fixed-wing aircraft just need to follow the path and reduce error as much as possible [3]. In addition to fixed-wing aircraft, helicopters are also introduced on the carrier to perform the tasks which are beyond the capability of fixed-wing aircraft, such as sea rescue, transportation, and antisubmarine warfare. One of the biggest advantages is that helicopters do not occupy the resource of runways, which reduces the waiting time of fixed-wing aircraft in the air [4]. Only an empty area of the flight deck is needed for a helicopter to land, and the mode of vertical landing is much safer than stopping by the arresting cable on the flight deck of a carrier [5].

In a typical combat mission, helicopters usually take off first to execute reconnaissance tasks, and then fixed-wing aircraft are launched in the air to attack enemy planes. After the combat mission is finished, fixed-wing aircraft return to the carrier and are maintained on the flight deck, and helicopters land on the specified empty area of flight deck. Unlike fixed-wing aircraft, the landing path of

helicopters is not regulated and can be determined autonomously, satisfying certain constraints [6]. At present, the path of helicopter landing on the carrier is determined by the pilot in advance. In this mode, the pilot watches the moving ideal landing point all the time and manipulates the helicopter. When the weather is good and the near space of the carrier is free, manual operation is enough to finish the landing task. However, if bad weather or a busy situation in the near space of the carrier occurs, this working mode is not so reliable, due to the poor visibility and the dynamical environment. To be specific, the ideal landing point is changing with the movement of carrier, and a no-fly zone is set on the space near the carrier. Additionally, specific angles of reaching the ideal landing point are regulated for the helicopter to avoid a collision with other returning fixed-wing aircraft and to reduce the influence of wind field. Those constraints increase the difficulties of searching a feasible landing path by men, and an automatic path planner for helicopters is imperative to ensure the efficiency and safety of the landing task on the carrier [7].

## 2. Literature Review and the Work of this Paper

The study on helicopter landing has been a hotspot in recent years. The estimation of position and altitude [8,9], landing in unusual conditions [10], and visualization [11,12] are the main concerns. In Reference [13], the movement state estimation method based on the vision image process for unmanned helicopters is proposed. In this method, a relative position to the landing pad and attitude estimation algorithm and a velocity and angular rate estimation algorithm are included to estimate the position, attitude, velocity, and angular rate with the vision image process data. Considering that it is difficult for a pilot to see obstacles or ground through snow or dust, a sensor detecting obstacles or ground inside aerosols has been designed in Reference [10]. The sensor can suppress the return signals from nearby aerosol scattering and has a sensitivity and dynamic range to detect obstacles or ground inside aerosol at the same time. To make an accurate landing, a vision-based navigation algorithm is developed to deal with the landing task in complex environments. The vision navigation system is integrated with algorithms of vision detection, target recognition, and navigation instruction calculation [11].

In the existing literature concerning path planning of helicopters, different situations are taken into account. In Reference [14], the helicopter is used for both the surveying and spraying of weeds in forest. This task is divided into two phases, and 2D and 3D path plans are both operated respectively with the rapidly exploring random tree (RRT) algorithm. The helicopter can also be applied in aerial photography. In this task, multiple points are set that the helicopter must pass through to take photos and shoot videos, and the optimal path is obtained by developing an improved probabilistic roadmap method (PRM) [15]. When a helicopter is used in the military, it must be guaranteed that the helicopter can avoid threats in low altitude areas [16] and can deal with emergency when one engine fails. In Reference [17], the landing trajectory of a multiengine helicopter in the event of a single engine failure is generated using the optimal control method. Time derivatives of thrust coefficients are treated as control variables, and constraints on rotor speed and thrust vector are imposed. The goal is to minimize the distance between the touchdown point and the original takeoff point, subject to impact speed limits at touchdown. Another important issue during helicopter landing is to reduce ground noise. In Reference [18], this problem is formulated into an optimal control problem that minimizes noise levels measured at points on the ground surface using equations of motion of three degrees of freedom. In summary, the studies of path planning for helicopters concentrate on the establishment of mathematical models and search algorithm designs in different tasks. Additionally, dividing the whole flight into several phases according to a specific mission also makes the problem easier to solve [19].

On the platform of flight deck operation on the carrier, path planning for aircraft taxiing and decision making for aircraft landing are concentrated on. The static obstacles (i.e., unemployed aircraft and island on the flight deck [20]), different states of wing (i.e., folded wings and unfolded wings [21]) and terminal constraints are taken into account in describing the path planning problem [22]. In the algorithm design, geometrical spatial search algorithms and swarm optimization algorithms are used

to obtain the optimal taxiing path. As to the landing task of carrier aircraft, the optimization of a landing sequence for a team of fixed-wing aircraft [23], the landing path determination for fixed-wing aircraft [24], and comparison between expert user heuristics and automatic planning tools [25] are given more attention. In Reference [23], a dynamic sequencing algorithm based on an ant colony optimization (ACO) algorithm was developed to optimize the landing sequence of aircraft, considering the landing failure of aircraft, which provides an intelligent tool for overall air traffic management on aircraft carriers. Due to the fuzziness of environmental information, a TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution)-based group decision-making method was proposed to assist the pilot determining the most reasonable landing path under various environments [24].

To the best of the authors' knowledge, there are no reported studies focused on path planning for helicopter landing on a carrier. Similar studies focus on path planning for helicopter landing on a moving platform [26,27]. In Reference [26], the trajectory planner is based on the Variational Hamiltonian and Euler-Lagrange equations, and a kinematic model of the helicopter is used to derive an optimal controller that is able to track an arbitrarily moving target and then land on it. In Reference [27], the landing procedure is divided into four stages, and the goal of each flight stage is different. Finally, the landing path is obtained by linear programming piecewise.

In this paper, the landing task of helicopters is divided into two phases, according to the distance between the helicopter and the ideal landing point, that is, approaching the carrier and landing on the flight deck. Then, the conceptual model is abstracted, which gives a general idea of solving the problem. The constraints by category and the cost functions in different flight phases are all included in the mathematical model. When designing the path planning algorithm, different search strategies are developed using the pigeon inspired optimization (PIO) algorithm, based on the feature of each flight phase. The PIO algorithm is a bioinspired hybrid metaheuristic [28] and was firstly proposed by Duan in 2014 [29], and the feasibility and superiority of the algorithm have been proved in image restoration problems [30] and model prediction control [31]. However, the PIO algorithm has not been applied in a multiphase path planning problem, and its performance needs to be further investigated.

The rest of the paper proceeds as follows. Section 2 describes the landing task of helicopters on a carrier. The mathematical model of the landing path planning problem is established in Section 3. The details of the path planning algorithm are depicted in Section 4. Experimental studies are reported in Section 5 and the concluding remarks are contained in the last section.

### 3. Description of the Landing Path Planning Problem for Helicopters

In this section, the background of the landing task for helicopters will be introduced, and the whole flight is divided into two phases. Then, the conceptual model solving the problem is proposed to present the idea and organize the elements that are taken into account in this problem.

#### 3.1. Division of the Flight of the Landing Task

The landing task of helicopter on the carrier specified in this paper can be described as follows: After the helicopter has finished the task in the air, it informs the air traffic control center on the carrier of the return message. Then, the carrier sails towards a certain direction with a constant velocity [32]. The helicopter keeps following the carrier at a safe altitude and then decreases its altitude to land on the ideal landing point on the flight deck. The whole flight can be divided into the following two phases:

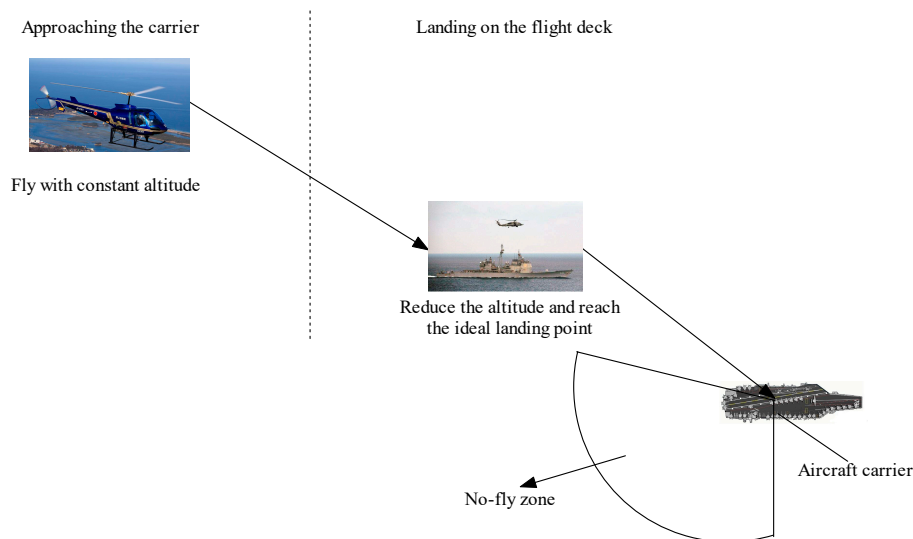
##### 1. Approaching the carrier ("approaching phase" for short for convenience in the rest of this paper)

The helicopter flies with a constant altitude in this phase. The goal is to minimize the horizontal distance between the helicopter and the carrier as soon as possible. In this phase, the distance between the helicopter and the carrier is relatively far, so the constraint of a no-fly zone is not imposed. After the distance is reduced to a certain value, the helicopter moves to the next flight phase.

## 2. Landing on the flight deck (“landing phase” for short for convenience in the rest of this paper)

The ideal landing point is located in the empty area of the center flight deck. The helicopter reduces its altitude and reaches the flight deck with the minimum position error. Note that the heave motion of the carrier is considered in this phase to reflect the change of altitude of the ideal landing point.

To get a better understanding of the above landing phases, the diagram of the helicopter returning is shown in Figure 1.

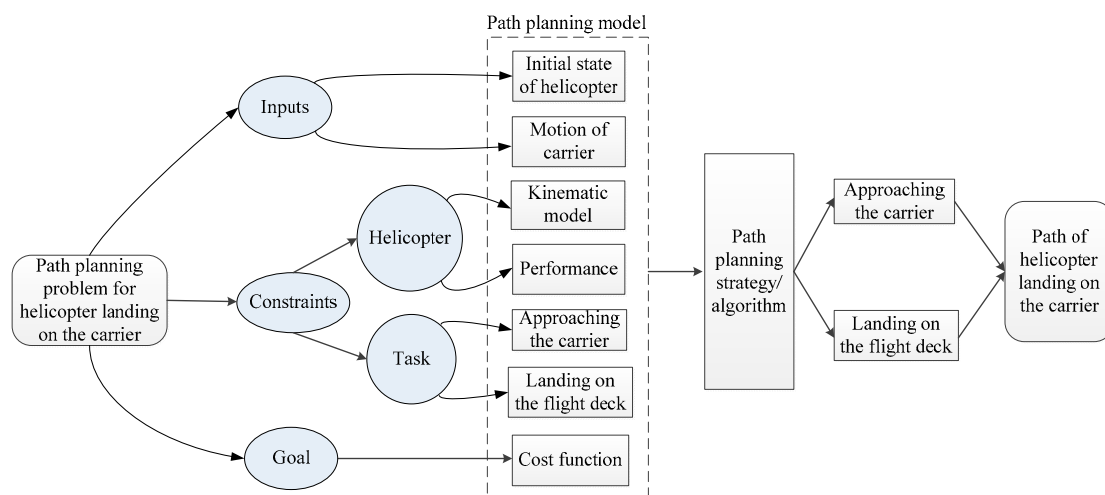


**Figure 1.** Description of the landing task for the helicopter.

In Figure 1, the content of each flight phase is shown. The no-fly zone is set at the end of the flight deck to avoid the helicopter colliding with the returning fixed-wing aircraft and to reduce the influence of wind field. The task of path planning is to generate a feasible landing path for the helicopter and guarantee landing safety.

### 3.2. Conceptual Model of the Path Planning Problem

In Section 3.1, the whole flight was divided into two phases, which provides a frame for solving the problem. On this basis, the conceptual model is proposed to organize the idea and elements of the problem, as shown in Figure 2.



**Figure 2.** Conceptual model of the problem.

In Figure 2, the problem is composed of three elements. The constraints are imposed on the helicopter and the task, respectively. The goal of the landing task is described by the cost function. In the path searching process, different strategies need to be developed to adapt to the situations. The above description summarizes the idea of solving the problem. Next, each element in Figure 2 will be explained in detail.

#### 4. Establishment of the Mathematical Model

According to the conceptual model, path planning for helicopter landing on the carrier can be formulated into an optimization problem. In this problem, under a given model of helicopter, the control variables are the velocities in each direction which need to be optimized. The constraints can be grouped into two categories, that is, constraints imposed on the control variables and the state of the helicopter. In the constraints of control variables, the performance of the helicopter is limited by the velocity and acceleration. As for the constraints of state of helicopter, they limit the position and flight direction of the helicopter, considering the characteristics of the environment and the requirements of the landing task. As the landing task has been divided into two phases, the optimization goal of each phase is not the same, and they are proposed based on the characteristics of each phase. Next, each element of the optimization problem will be formulated into mathematical forms.

##### 4.1. Kinematic Model and Performance Constraints of Helicopter

In this study, a simplified kinematic model of helicopter presented in Reference [27] is used, and a more complicated form of equations can be further considered in the design of a landing controller.

Firstly, a coordinate system must be defined to describe the motion of the helicopter and the carrier. The coordinate origin  $O$  is fixed and is defined as the initial position of the ideal landing point, and the axis  $Ox$  points to the direction where the carrier sails. The axis  $Oz$  is vertically downward and the axis  $Oy$  can be determined by the right hand rule. Under the above coordinate system,  $(x, y, z)$  and  $(V_x, V_y, V_z)$  are the position and the velocity of helicopter in each direction, and  $\varphi$  is the yaw angle.

In this path planning problem,  $x, y, z, \varphi$  are the state variables and can be denoted as the vector  $\mathbf{x} = \begin{bmatrix} x & y & z & \varphi \end{bmatrix}$ .  $V_x, V_y$  and  $V_z$  are the control variables to be optimized and can be expressed as  $\mathbf{u} = \begin{bmatrix} V_x & V_y & V_z \end{bmatrix}$ . Note that in different flight phases, the control variables are not always the same. For example, when the helicopter is approaching the carrier, the flight altitude remains unchanged. In this phase,  $V_z = 0$  and only  $V_x$  and  $V_y$  are the control variables. While in the landing phase, all of the three control variables need to be optimized to make a precise landing.

In the landing task, the helicopter must fly within its maneuverability. The performance constraints imposed on the helicopter can be denoted as follow:

$$V_x \leq V_x^{\max} \quad (1)$$

$$V_y \leq V_y^{\max} \quad (2)$$

$$V_z \leq V_z^{\max} \quad (3)$$

$$a_{xy} \leq a_{xy}^{\max} \quad (4)$$

$$a_z \leq a_z^{\max} \quad (5)$$

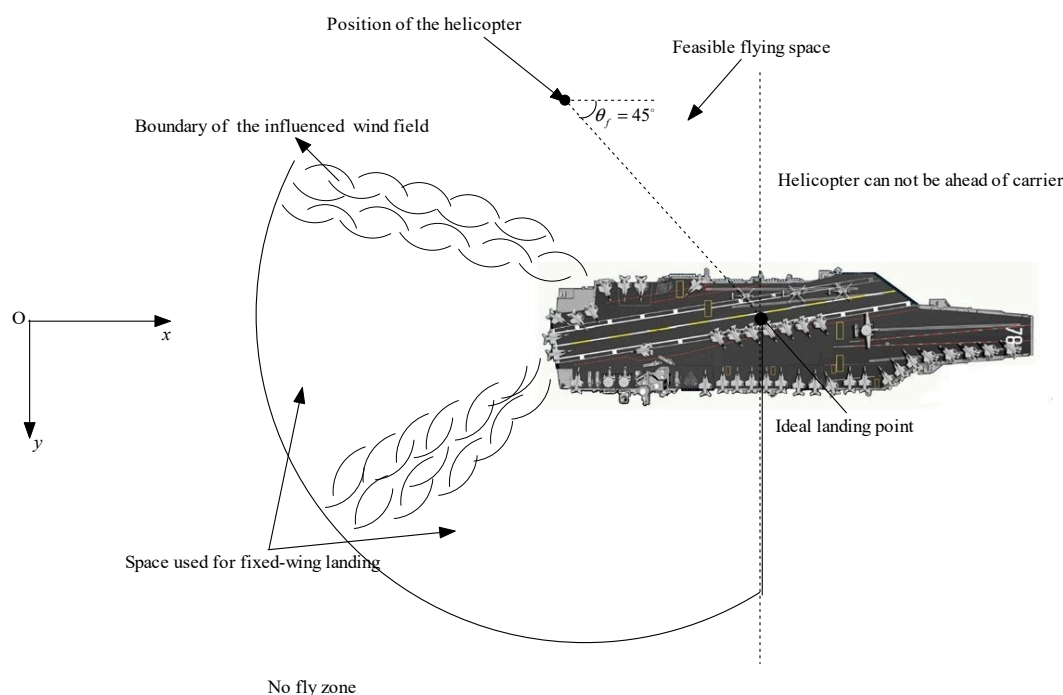
In the above five equations, the flight velocity in each direction is constrained by Equations (1)–(3). Equations (4) and (5) are added to limit the acceleration in the plane  $xOy$  and axis  $Oz$ , and  $a_{xy} = \sqrt{\dot{V}_x^2 + \dot{V}_y^2}$ .

#### 4.2. Constraints Regarding the Landing Task

In the landing task, certain constraints must be imposed on the state of helicopter to meet the task requirements. These constraints are described as follow:

##### 1. Determination of the feasible flying space

To ensure the safety of the landing task, the no-fly zone is set to avoid the helicopter disturbing the normal landing of the fixed-wing aircraft or even colliding with the fixed-wing aircraft. Additionally, the wind field in the near space of the carrier also affects the landing of the helicopter. The position of the helicopter cannot be ahead of the carrier in the  $Ox$  direction, or the landing task will fail. Those constraints limit the position of the helicopter and are described in Figure 3.



**Figure 3.** Diagram of feasible flying space in the landing task.

In Figure 3, the feasible flying space only occupies a relatively small part of the space near the carrier, which adds the difficulty of searching for the optimal landing path. The constraint of the direction of reaching the ideal landing point will be described later on.

##### 2. Direction of reaching the ideal landing point

When the helicopter is near the flight deck, the helicopter is required to reach the ideal landing point with the constraint of  $\theta_f = 45^\circ$  to conform to the landing rules [33], as shown in Figure 3. Note that this constraint is proposed based on the assumption that the carrier sails in the opposite direction of the wind field. Under this condition, the wind in the two sides of the carrier is symmetrical, and the ideal direction for the helicopter reaching the landing point is set as  $\theta_f = 45^\circ$ . In other cases of asymmetric wind, the ideal direction must be decided according to the wind graph. The value of  $\theta$  during landing can be calculated by the following equation:

$$\theta = \tan^{-1}\left(\frac{y_t - y}{x_t - x}\right) \quad (6)$$



where  $(x, y)$  is the current position of helicopter, and  $(x_t, y_t)$  is the position of the ideal landing point. The above constraint can be denoted as the following form, where  $e_{\theta_{\max}}$  is the maximum permitted error of  $\theta_f$ :

$$e_{\theta} = |\theta(t_f) - \theta_f| \leq e_{\theta_{\max}} \quad (7)$$

#### 4.3. Determination of the Cost Function

The helicopter should finish the landing task as soon as possible after it performs the specific task in the air. In each flight phase, the goal is not exactly the same. To be specific, when the helicopter is approaching the carrier, the prime goal is to reduce the distance between the helicopter and the carrier. To satisfy the constraint in Equation (7) more easily, the value of  $\theta$  becomes important, as the distance is smaller. The cost function in the approaching phase can be written as:

$$J_1 = dis\_hor + t_1 \cdot n \cdot e_{\theta} \quad (8)$$

$J_1$  is the cost function of the approaching phase, and  $dis\_hor$  is the horizontal distance between the helicopter and the ideal landing point.  $n$  is the serial number of path point, and  $t_1$  makes the two items in Equation (8) have the same order of magnitude. Note that Equation (8) is a form of dynamic weight function. With the increasing of flight time, the value of  $\theta$  will be given more attention.

In the landing phase, the terminal position error between the helicopter and the ideal landing point is important. Moreover, to reduce the heavy impact at the landing moment, the difference of vertical velocity between the helicopter and the ideal landing point is expected to be smaller. The cost function in this phase can be denoted as:

$$J_2 = dis + t_2 \cdot |V_z(t_f) - V_{zc}(t_f)| \quad (9)$$

$J_2$  is the cost function in the landing phase, and  $dis$  is the distance between the helicopter and the carrier in 3D space.  $V_{zc}$  is the vertical velocity of the ideal landing point, and  $t_2$  makes the two items in Equation (9) comparable. Equation (9) gives a comprehensive consideration of both the landing accuracy and safety.

### 5. Path Planning Algorithm Design for Helicopter Landing

As the whole flight has been divided into two phases, a multiphase path planning strategy will be developed in this section. Then, the general principle of the PIO algorithm is introduced, based on which the path planning algorithm is proposed. The flow of the algorithm is also presented.

#### 5.1. The Multiphase Path Planning Strategy

The path planning strategy is developed according to different flight phases, and the details are presented below:

##### 1. Strategy in the approaching phase

Considering that the helicopter is far from the carrier and the environment is changing, only the motion of helicopter in a short time window of future (denoted as  $T_w$ ) is planned in one step of search, assuming that the discrete time interval is  $\Delta t$ , and the number of path point in one step of search (denoted as  $N_w$ ) can be determined ( $N_w = T_w / \Delta t$ ). Based on the ideas of model predictive control [34], this “short-term” planning strategy will last before the horizontal distance between the helicopter and the carrier is reduced to a certain value. Note that the heave motion of the carrier is not considered in this phase because it will not have an influence on the result.

##### 2. Strategy in the landing phase

In this phase, the helicopter is near the carrier. As the motion of the carrier is known, the remaining unplanned path can be obtained all at once. To reduce landing time, the helicopter must decrease its altitude as soon as possible. This makes the helicopter fly with  $V_z^{\max}$  in most of the flight time, and only the values of  $V_z$  during a certain period of time, which is before the helicopter touches the flight deck, need to be optimized. This operation reduces the computational load of online planning and makes the landing task more efficient at the same time.

To reduce the terminal position error, the Chebyshev pseudo spectral method is used to generate the collocation points [35]. The collocation points are distributed according to the value of  $T_k$ , as shown in Equation (10):

$$T_k = \cos\left(\frac{(N_c - k) \cdot \pi}{N_c}\right) (k = 0, 1, 2, \dots, N_c) \quad (10)$$

The number of collocation points is  $N_c + 1$ . The Chebyshev points are dense at both ends and sparse in the middle. This feature just satisfies the demand that there should be more collocation points at the end of landing path to reduce the position error. Note that  $T_k \in [-1, 1]$ , and it should be converted to the time interval  $[t_0, t_f]$  using the following equation:

$$t_k = \frac{t_f - t_0}{2} \cdot T_k + \frac{t_f + t_0}{2} \quad (11)$$

Equation (11) demonstrates that only the control variable at the moments  $t_k$  ( $k = 0, 1, \dots, N_c$ ) is optimized, and the values of control variables at other moments (denoted as  $t_i$ ) can be obtained by linear interpolation, as expressed in Equation (12) (take  $V_{xti}$  ( $t_k < t_i < t_{k+1}$ ) as an example):

$$V_{xti} = \frac{V_{xt_{k+1}} - V_{xt_k}}{t_{k+1} - t_k} \cdot (t_i - t_k) + V_{xt_k} \quad (12)$$

## 5.2. A Brief Introduction of the Pigeon Inspired Optimization (PIO) Algorithm

The pigeon inspired optimization algorithm is a kind of bioinspired hybrid metaheuristic. In recent years, the bioinspired hybrid metaheuristic has attracted a lot of attention as an effective method to solve difficult real-world optimization problems because, in those algorithms, the solution quality and the computation load can be made a good balance, and an optimal or near optimal solution can be obtained in short time. The studies on the bioinspired hybrid metaheuristic have turned to problem-oriented, that is, an algorithm is applied or improved, based on the characteristics of the specific problem [36]. For example, to solve the capacitated network design problem (CNDP), a robust optimization model based on multiband robustness was proposed, and a hybrid primal heuristic was developed [37]. In this algorithm, a randomized fixing strategy inspired by ant colony optimization and an exact large neighborhood search were combined, and solutions of extremely high quality associated with low optimality gaps can be obtained by this new algorithm. Another case is to minimize the electricity cost in electric grids. To achieve this goal, hybridization of the genetic algorithm (GA) and PIO algorithm (HGP) in demand side management were proposed to apply for residential load management, and the performance of HGP is better than GA and PIO in optimizing the fitness function [38]. In the path planning problem, a predator-prey pigeon inspired optimization (PPPIO) algorithm was proposed to generate the three-dimensional path for uninhabited combat aerial vehicles (UCAV) in a dynamic environment [39]. In the PPPIO algorithm, the prey-predator concept is adopted to improve global best properties and to enhance the convergence speed of the standard PIO algorithm, and comparative simulation results verified the efficiency of the proposed PPPIO algorithm in solving the UCAV three-dimensional path planning problem.

As for the PIO algorithm, it is motivated by the self-organized homing behavior of pigeons. To be specific, pigeons can always find their homes easily by using their unique homing tools, that is, magnetic fields, the sun, and landmarks. In the PIO algorithm, there are two operators to change



the position of pigeons. Next, the details of the PIO algorithm will be explained, combining the characteristics of the path planning problem for helicopters landing on the carrier.

### 1. The map and compass operator

In the PIO algorithm, each pigeon  $i$  has its position  $X_i$  and velocity  $V_i$ , and  $X_i$  and  $V_i$  are both  $D$ -dimension vectors according to the scale of problem. In each iteration,  $X_i$  and  $V_i$  are updated with the following equations:

$$V_i^{t+1} = V_i^t \cdot e^{-R(t+1)} + rand \cdot (X_g - X_i^t) \quad (13)$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad (14)$$

where  $t$  is the times of iteration,  $R$  is the operator factor,  $rand$  is a uniform number in the interval  $[0, 1]$ , and  $X_g$  is the current global best position. In the path planning problem studied in this paper, the position  $X_i$  denotes a path consisting of a certain number of points, and the number of points in a path is the dimension of  $X_i$  and is determined by the phase that the path belongs to. In the approaching phase  $D = N_w$ , and in the landing phase  $D = N_c + 1$ .  $V_i$  is the disturbing operator that changes the value of the path point, and  $X_g$  represents the control variable vector corresponding to the minimal value calculated by the cost function in Equations (8) or (9), according to the different phases of the landing task.

### 2. Landmark operator

When the pigeons are closer to their home (after certain times of iterations), the landmark operator is used in the rest of the journey. With the landmark operator, the number of pigeons is decreased by half after every iteration. Additionally, the center of the pigeons' positions is referenced in the landmark operator to make the pigeons reach their home quickly. Assuming the center of the pigeons' positions at the  $t$ th iteration is  $X_c^t$ , the rule of updating the position of pigeon  $i$  can be written as the following equations:

$$N_p^t = \frac{N_p^{t-1}}{2} \quad (15)$$

$$X_c^t = \frac{\sum X_i^t \cdot fitness(X_i^t)}{N_p^t \sum fitness(X_i^t)} \quad (16)$$

$$X_i^{t+1} = X_i^t + rand \cdot (X_c^t - X_i^t) \quad (17)$$

where  $N_p^t$  is the number of pigeons at the  $t$ th iteration, and  $X_c^t$  is the geometrical center of the pigeons.  $fitness(X_i^t)$  is the fitness value of pigeon  $i$ , which can be calculated by Equation (8) or Equation (9), according to the different landing phase, and  $rand$  is a uniform number in the interval  $[0, 1]$ . In the landmark operator, the center of all pigeons is regarded as the destination in each iteration. Half of all the pigeons with the worst fitness values will be abandoned in the next iteration, and the rest of the pigeons that are close to the destination will fly home quickly. In the landmark operator, the number of spare paths is reduced by half after an iteration, and  $X_c^t$  is the control variable vector corresponding to the mean fitness value of all the spare paths. Similar to the map and compass operator, the value of the control variable is updated by adding a disturbing operator on the old value.

### 5.3. Process of the Multiphase Path Planning Algorithm

The path planning strategy and PIO algorithm are integrated into the path planning algorithm design. The pseudocode is presented below (Algorithm 1), and the corresponding flow chart is summarized in Figure 4.

**Algorithm 1:** PIO-based algorithm for helicopter landing on the carrier

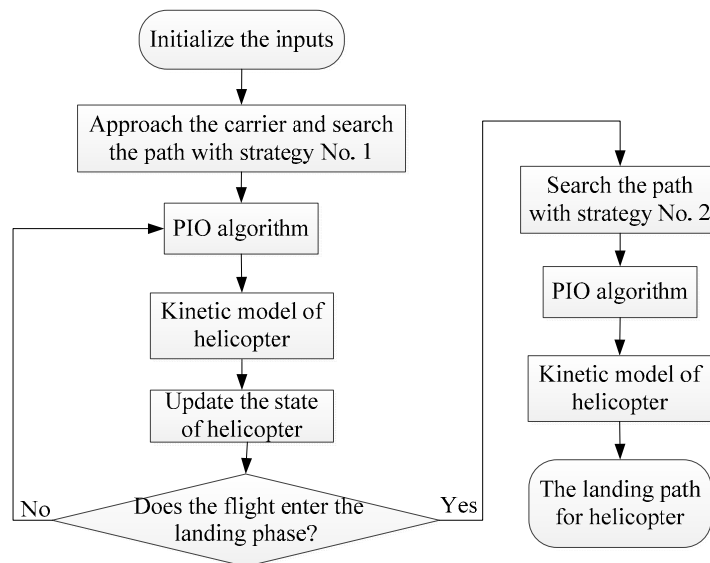
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1: initialization: length of time window  $T_w$ , time interval  $\Delta t$ , times of iteration in map and compass operator  $N_{c1}$ , times of iteration in landmark operator  $N_{c2}$ , scale of problem  $N_p$ , other parameters in PIO algorithm, helicopter performance, initial path  $X_i$  and velocity  $V_i$ 
2: calculate the fitness value of each path and determine the global best  $X_g$ .
3: map and compass operator
4: for  $t_1 = 1 : N_{c1}$ 
5:   for  $i = 1 : N_p$ 
6:     calculate  $X_i$  and  $V_i$ 
7:   end
8:   for  $j = 1 : D$ 
9:     if  $X_i$  is beyond its permitted range
10:      set  $X_i$  as the closest threshold
11:    end
12:  end
13:  calculate the fitness value of each updated path and determine the current global best  $X_g$ .
14: end
15: landmark operator
16: for  $t_2 = 1 : N_{c2}$ 
17:    $N_p = N_p/2$  (keep half of the spare paths with better fitness value and abandon the other half)
18:   for  $k = 1 : N_p$ 
19:     calculate  $X_c$  of the each remaining paths
20:     update  $X_k$ 
21:   end
22:   for  $l = 1 : D$ 
23:     if  $X_l$  is beyond its permitted range
24:      set  $X_l$  as the closest threshold
25:    end
26:  end
27:  calculate the fitness value of each updated path.
28: end
29: output:  $X_g$  is returned as the global optimal control variables and the corresponding path is the landing path for helicopter.

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**Figure 4.** The flow of path planning algorithm.

In Figure 4, path planning strategy No. 1 is applied in the approaching phase, and path planning strategy No. 2 is used in the landing phase to obtain the remaining unplanned path all at once. PIO algorithm is adopted in both of the two phases to search the landing path for helicopter.

## 6. Results

To validate the effectiveness of the established mathematical model and the multiphase path planning algorithm in solving the problem of helicopter landing on the carrier, three experiments under different situations are conducted. In the first case, the carrier is static during the whole landing process of the helicopter, and the landing path of the helicopter under this situation is obtained. In the second case, the carrier always moves with a velocity of  $V_c = 10$  m/s. Based on the setting in case 2, the heave motion of the carrier is taken into account in case 3, which increases the difficulty of generating the landing path. In all three cases, the starting point of the helicopter and the ideal landing point are set as  $(-800, -600, -80)$  and  $(0, 0, 0)$ , respectively.

The parameters used in the PIO algorithm are set according to the scale of the problem and are based on Reference [30] and Reference [31] to result in the best performance, as presented in Table 1. The constraints on helicopter performance and landing task are set by referring to Reference [27] and Reference [33], and they are given in Table 2. All the experiments are conducted on a desktop with Intel Core i7-3370 3.40 GHz with MATLAB R2017a.

**Table 1.** Parameters setting in pigeon inspired optimization (PIO) algorithm.

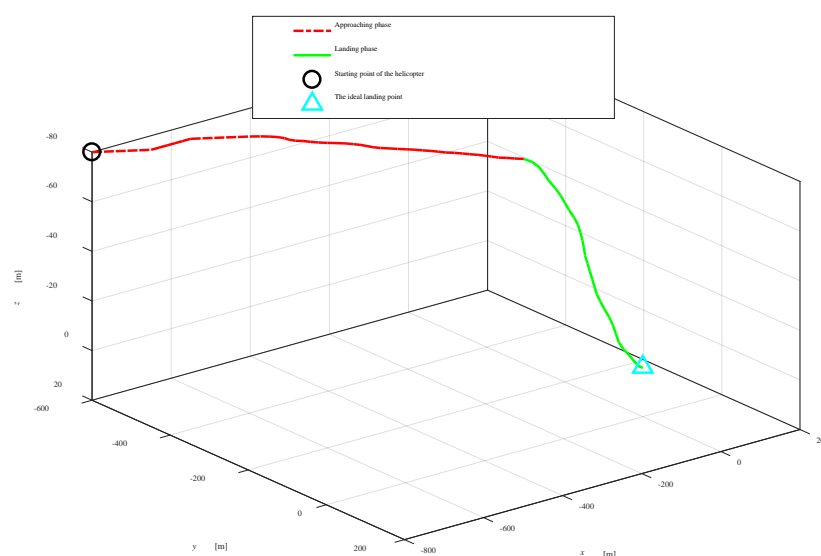
Parameter	$T_w$	$\Delta t$	$N_p$	$R$	$N_{c1}$	$N_{c2}$
Value	5 s	1 s	1000	0.2	20	30

**Table 2.** Constraints of helicopter performance and landing task.

Item	$V_x^{\max}$	$V_y^{\max}$	$V_z^{\max}$	$a_{xy}^{\max}$	$a_z^{\max}$	$e_\theta$
Value	20 m/s	10 m/s	3 m/s	3 m/s <sup>2</sup>	1 m/s <sup>2</sup>	5 deg

### 6.1. Helicopter Landing on the Static Flight Deck

In this case, the carrier does not move during the landing task of the helicopter. With the settings in Tables 1 and 2, the landing path of the helicopter is obtained with the proposed method, as shown in Figure 5.



**Figure 5.** The landing path of the helicopter when the carrier is static.

In Figure 5, the curves with different colors denote different flight phases of the helicopter. The helicopter keeps its altitude when it is far from the carrier. As the distance decreases, the helicopter reduces the flight altitude and finally lands on the flight deck. To get a better understanding of the result, the state of the helicopter and the control variable during the landing task are presented in Figures 6 and 7 respectively.

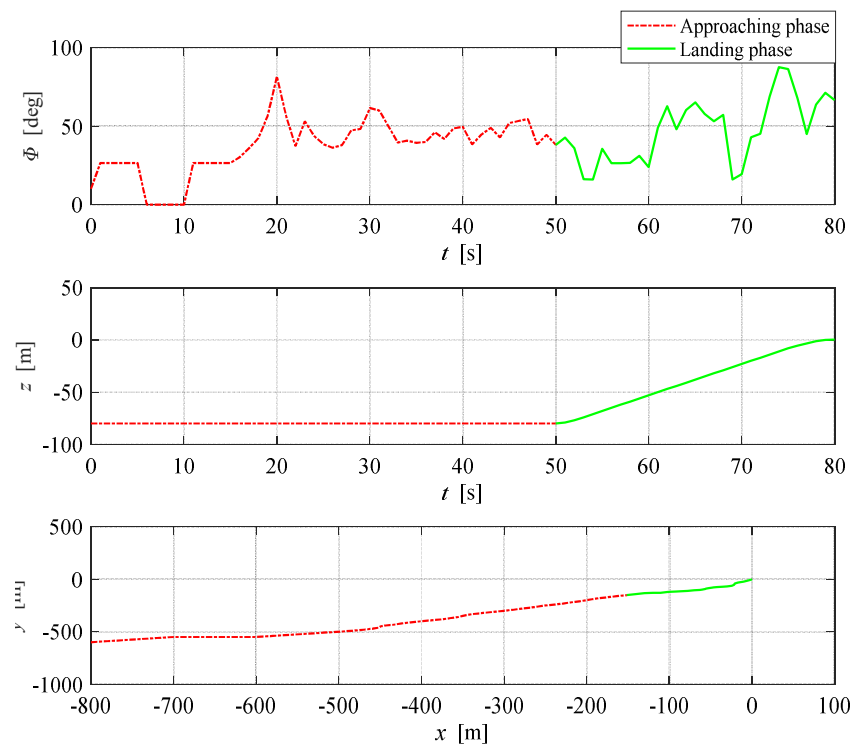


Figure 6. State of the helicopter during the landing task.

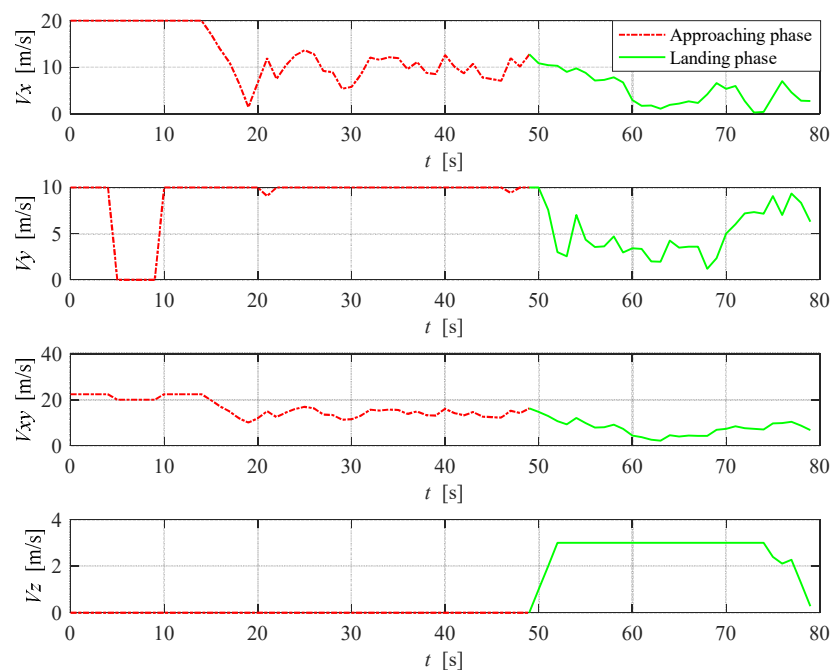


Figure 7. Velocity of the helicopter during the landing task.

In Figure 6, the motion of the helicopter in the  $xOy$  plane and  $Oz$  axis are given, respectively. In the approaching phase, the value of  $z$  remains unchanged, which is consistent with the fourth subplot in Figure 7. In the landing phase,  $V_z$  keeps to the maximum most of the time to make the helicopter reach the ideal landing point as soon as possible. In general, the same conclusion can be reached from Figure 6 or Figure 7, thus making those results reasonable. The terminal state of the helicopter and the ideal state are listed in Table 3.

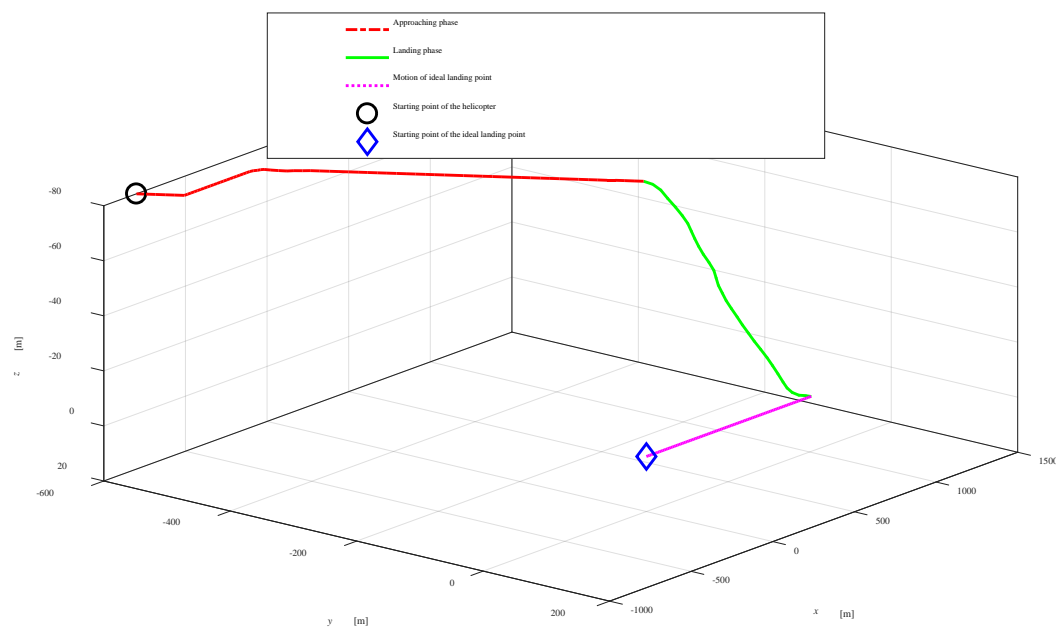
**Table 3.** The terminal state of the helicopter and the ideal state.

Item	$x$ (m)	$y$ (m)	$z$ (m)	$\varphi$ (deg)	$V_x$ (m/s)	$V_y$ (m/s)	$V_z$ (m/s)	$\theta$ (deg)
Actual	−0.009	−0.010	−0.081	66.7	2.717	6.309	0.278	50.0
Ideal	0	0	0	-	-	-	0	45
Error	−0.009	−0.010	−0.081	-	-	-	0.278	5.0

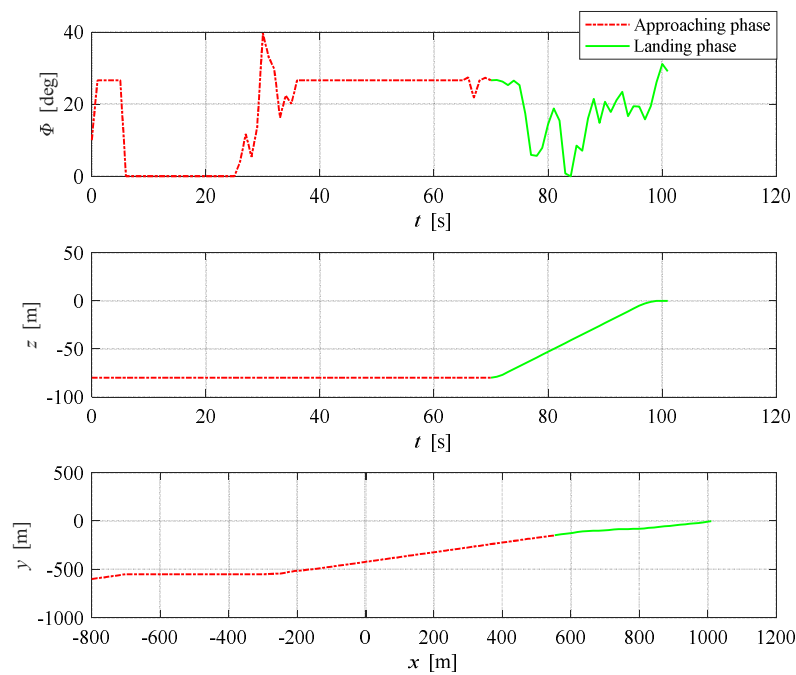
The symbol “-” means that there is no ideal value for this item. In Table 3, the deviation between the actual and ideal landing point is small, and the relative vertical velocity between the helicopter and the carrier is 0.278 m/s, which can reduce the impact on the helicopter and the carrier. Additionally, the direction of reaching the ideal landing point also meets the constraint. The above results demonstrate that the helicopter can land on the static ideal landing point, and the generated path satisfies various constraints to ensure flight safety.

## 6.2. Results of Landing on the Moving Flight Deck

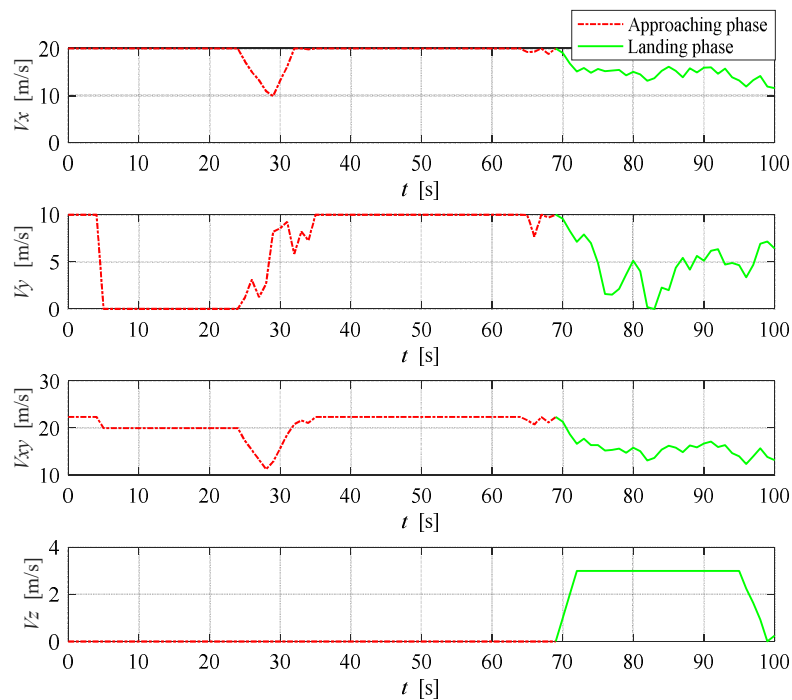
In this experiment, the carrier is set to move with the velocity of  $V_c = 10$  m/s, and other settings are the same as those in case 1. The landing path of the helicopter, the state, and the control variable during flight are presented from Figures 8–10.



**Figure 8.** Landing path of the helicopter and motion of the ideal landing point.



**Figure 9.** State of the helicopter in the landing task considering the moving of the carrier.



**Figure 10.** Velocity of the helicopter in the landing task considering the moving of the carrier.

Compared to the results in case 1, the helicopter spent more time to finish the landing task. The helicopter can track the movement of the ideal landing point and finally land on it. In the landing phase,  $V_z$  is accelerated to  $V_z^{\max}$  with the shortest time at the beginning, keeps with  $V_z^{\max}$  most of the time, and decreases gradually in the last several seconds. This mechanism can play the flight performance and reduce the landing time of the helicopter. To check the position error and the direction of reaching the ideal landing point, the terminal state of the helicopter and the ideal state are listed in Table 4.



**Table 4.** Comparison between the actual state of the helicopter and the ideal state.

Item	$x$ (m)	$y$ (m)	$z$ (m)	$\varphi$ (deg)	$V_x$ (m/s)	$V_y$ (m/s)	$V_z$ (m/s)	$\theta$ (deg)
Actual	1009.931	−0.077	−0.078	29.1	11.537	6.416	0.244	48.2
Ideal	1010	0	0	-	-	-	0	45
Error	−0.069	−0.077	−0.078	-	-	-	0.244	3.2

In Table 4, the small position error and the relative vertical velocity make the helicopter land precisely. Additionally, the direction of reaching the ideal landing point satisfies the constraint. The above results further explain the validity of the proposed path planning method for helicopter landing.

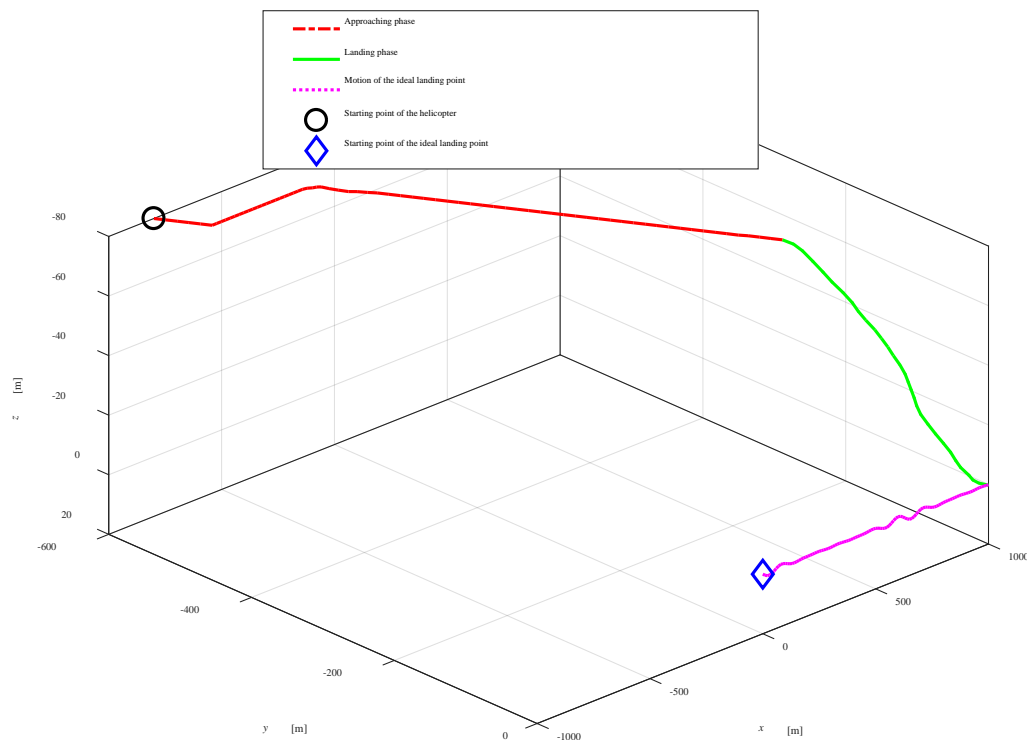
### 6.3. Formatting of Mathematical Components

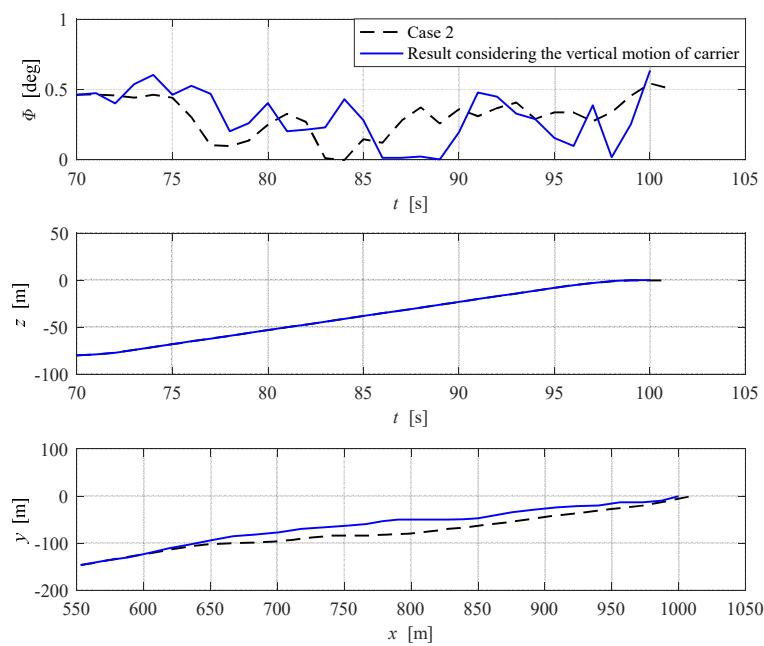
In a real situation, the sea water will move the carrier up and down, which makes the ideal landing point change in the  $Oz$  axis. In this experiment, the heave motion of the carrier is considered, based on the settings in case 2. The heave motion of the carrier can be represented by a sum of sine waves [40], which can be denoted as:

$$h(t) = 0.2172 \cdot \sin(0.4t) + 0.4714 \cdot \sin(0.5t) + 0.3592 \cdot \sin(0.6t) + 0.2227 \cdot \sin(0.7t) \quad (18)$$

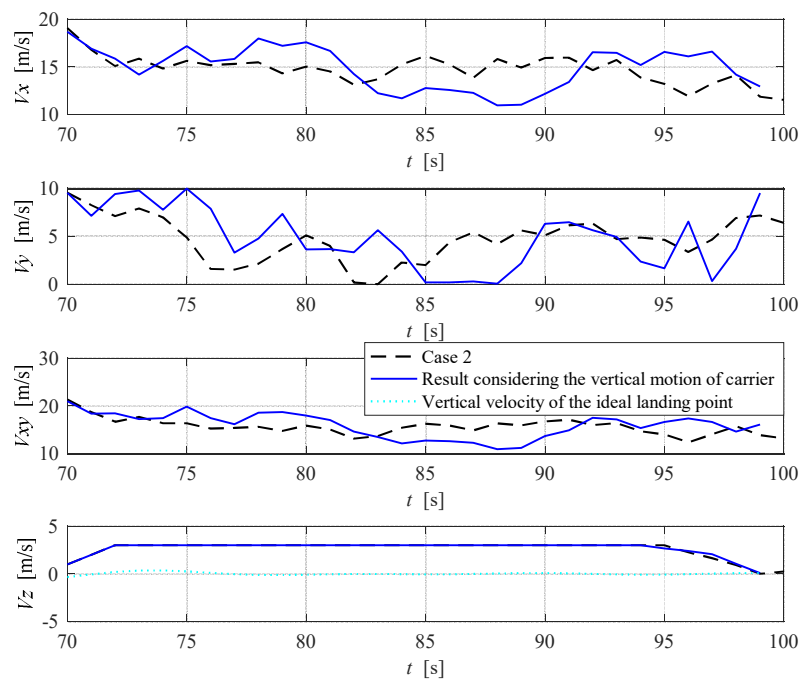
where  $h$  is the position of the ideal landing point in the  $Oz$  axis, and  $t$  is the current flight time.

As was explained in Section 4.1, the heave motion of the carrier is not considered in the approaching phase, and the path planning results of the approaching phase in case 2 and 3 are the same. For this reason, only the path planning results in the landing phase are drawn when making a comparison. The path planning results are shown from Figures 11–13.

**Figure 11.** Landing path of the helicopter and 3D motion of the ideal landing point.



**Figure 12.** State of the helicopter in the landing task, considering the 3D motion of the carrier.



**Figure 13.** Velocity of the helicopter in the landing task, considering the 3D motion of the carrier.

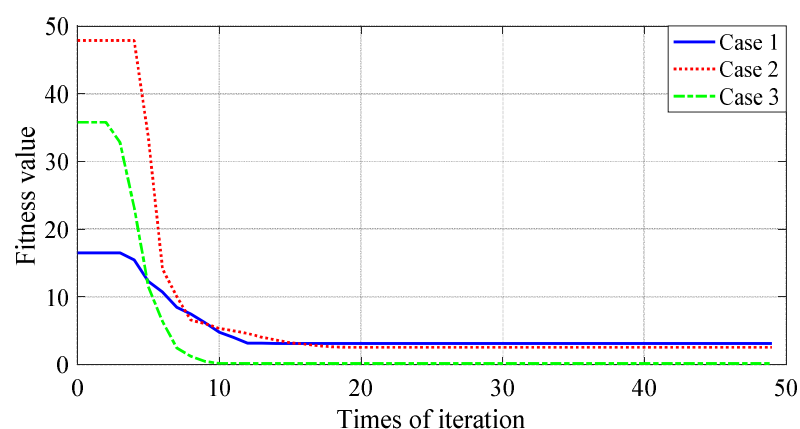
Compared to Figure 8, the carrier has a 3D motion in Figure 11, which makes the ideal landing point change in the  $Oz$  axis. Under this situation, the helicopter can still reach the ideal landing point and finish the landing task. Compared to case 2, the landing time is reduced by several seconds in case 3. Furthermore, the curves representing the vertical motion in case 2 and 3 are close. This demonstrates that the helicopter flies for as less time as possible to finish the landing task. The vertical velocity of the carrier is much smaller than that of the helicopter. The terminal states corresponding to case 3 are presented in Table 5.

**Table 5.** Terminal states corresponding to case 3.

Item	$x$ (m)	$y$ (m)	$z$ (m)	$\varphi$ (deg)	$V_x$ (m/s)	$V_y$ (m/s)	$V_z$ (m/s)	$\theta$ (deg)
Actual	999.992	−0.008	−0.062	36.4	12.938	9.538	0.089	45.5
Ideal	1000	0	0.101	-	-	-	0.089	45
Error	−0.008	−0.008	−0.163	-	-	-	0	0.5

In Table 5, the position error in the  $Oz$  axis increases, compared to the same item in Tables 3 and 4. This is because the altitude of the ideal landing point is changing in case 3, which makes it difficult to reach the ideal terminal state precisely. Note that the vertical motions of the helicopter and the ideal landing point are almost in synchrony, and the impact can be avoided to the greatest degree. Other items in Table 5 meet the constraint and ensure a precise landing path.

To demonstrate the variation of fitness value during iterations in the landing phase, the best fitness value of each iteration in all three cases is drawn respectively, as shown in Figure 14.

**Figure 14.** The best fitness value of each iteration.

The fitness values of the three cases can all converge within 20 times of iteration, thus verifying the fast convergence of the PIO algorithm. Note that Equation (9) is regarded as the fitness value in the landing phase, and the fitness value in case 3 is the smallest because the vertical motions of the helicopter and the ideal landing point are almost in synchrony, which makes the second item of Equation (9) almost negligible.

## 7. Conclusions

The path planning problem for helicopter landing on the carrier is addressed in this paper. Literature investigation shows that the path planning problem for helicopters is important and there is no reported study concentrating on the landing path planning problem on the carrier.

Firstly, the background of helicopter landing on the carrier is introduced, and the whole flight is divided into two phases according to different goals of each phase, that is, the approaching phase and the landing phase. The feature of each phase is described, and the conceptual model of the path planning problem is abstracted on this basis, which presents a general frame and idea of solving the problem. When establishing the mathematical model, the constraints are classified into two categories, that is, regarding the helicopter and regarding the landing task. The kinematic model and the performance of the helicopter are considered, and the no-fly zone and the terminal constraint are defined, taking into account the influence of the fixed-wing aircraft and the wind field. The goal is to reduce the terminal position error and the heavy impact between the helicopter and the carrier to ensure a precise and safe landing.

When searching the landing path, a multiphase path planning algorithm is developed to adapt to the environment in different flight phases, and the PIO algorithm is used to obtain the path in

both phases. In the experimental studies, three situations are considered to explain the validity of the proposed path planning method. In summary, the results demonstrate that the helicopters can all reach the ideal landing point with reasonable landing paths and a small position deviation. The landing safety is also guaranteed by meeting various constraints and reducing the relatively vertical motion between the helicopter and the carrier.

The main contribution of this paper is to establish a conceptual model and the mathematical model of the path planning problem for helicopter landing on the carrier. A multiphase path planning algorithm (MPPIO) is also developed to solve this problem. The modeling idea proposed in this paper can also be applied to other similar tasks for helicopters. In the future, a more complicated model would be considered to describe the motion of the helicopter, and quantitative description of wind field is needed to calculate the influence on the helicopter. Moreover, a landing controller for the helicopter is also expected to track the landing paths generated in this paper under various situations.

**Author Contributions:** Conceptualization, Y.W. and J.X.; methodology, H.H. and Y.W.; software, H.H. and Q.S.; validation, H.H., Y.W. and Q.S.; formal analysis, J.X.; investigation, Y.W.; resources, J.X.; data curation, Q.S.; writing—original draft preparation, H.H.; writing—review and editing, Y.W.; visualization, Q.S.; supervision, J.X.; project administration, Y.W.; funding acquisition, Y.W.

**Funding:** This research was funded by Fundamental Research Funds for the Central Universities with the project reference number of 106112017 CDJXY320003.

**Conflicts of Interest:** The authors declare no conflict of interest.

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