UAV Flight Performance Optimization Based on Improved Particle Swarm Algorithm

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Abstract. As the energy problem becomes more and more serious, it is necessary to do research on energy saving. In order to achieve the desired height economically and quickly, the two key factors of fuel consumption and time cost are considered. First, the mathematical model of UAV's climbing trajectory is established, the fuel consumption and time cost are considered as the performance optimization indexes. Second, the UAV's performance optimization method based on the improved particle swarm algorithm is proposed, then the problem of UAV's performance optimization is turned into the problem of constrained multi-parameter optimization, and the climbing trajectory with the optimal comprehensive index is determined. Finally, the proposed method is used in a certain type of UAV, and the simulation results show, compared with the conventional method, the proposed method saves more operation costs and has better superiority.

Keywords: UAV, climbing trajectory, performance optimization, improved particle swarm algorithm.

1 Introduction

In the recent years, the energy problem is becoming more and more serious, and the aerial fuel's price is keeping increasing, fuel saving has became one of the important goals of the flight performance optimization, so it is necessary to study how to improve the operating efficiency and decrease the time cost are very important. As the flight velocity, fuel consumption and time cost of the climbing trajectory have great influence on the whole flight process, the climbing trajectory is taken as the research object. The task of the climbing trajectory performance optimization is to design the best reference climbing trajectory.

There are some research results in trajectory performance optimization. An optimization technique based on the improved genetic algorithm was studied to calculate the fastest climbing trajectory[1], A genetic algorithm was used to design the optimization trajectory in the vertical flight in order to saving the fuel[2].But all the methods are devoted to find the optimization trajectory based on single index, it is difficult to achieve the goal that get the shortest climbing time and the least fuel consumption in the same time.

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The rate of UAV's fuel consumption increases rapidly with the velocity increasing. If only use the fastest climbing rate as the optimization performance index may lead to the climbing rate becomes too fast, and the fuel consumption becomes too high; Contrary to the above situation, if only use the least fuel consumption as the optimization performance, the climbing rate becomes too slow, and the climbing time becomes long. As the result, the climbing time and the fuel consumption are comprehensively considered in this paper, and the weighted sum (comprehensive operation cost) are used as the performance index to optimize the UAV's climbing trajectory.

The entire climbing trajectory can be divided into several parts according to the constant attitude Δh , the parameter of each height is optimized using the particle swarm algorithm. Particle swarm optimization (PSO) is an optimization method based on the swarm intelligence, it is widely used in various optimization fields as it has following advantages: flexible, efficient and easy to find the global optimal solution[3,4]. An improved particle swarm optimization (IPSO) is used to optimize the UAV's climbing trajectory in this paper, and the optimal reference climbing trajectory is determined according to the specific optimization task.

2 Mathematic Model

Assume the UAV doing no-sideslip particle motion in this period, and ignore the influence of the wind, the UAV's dynamic equations are:

$$m\frac{dv}{dt}=T\cos\alpha-L\sin\alpha-D-mg\sin\gamma \tag{1}$$

$$mv\frac{d\gamma}{dt}=T\sin\alpha+L\cos\alpha-mg\cos\gamma \tag{2}$$

and the kinematic equations are:

$$\frac{dx}{dt}=v\cos\gamma \tag{3}$$

$$\frac{dm}{dt}=q_h \tag{4}$$

In the above equations, m is the weight of the UAV, x and h are the horizontal voyage and the climb height respectively, v is the airspeed of the UAV (As ignoring the influence of the wind, the airspeed is the ground speed) , θ , α and γ are pitch angle, angle of attack and flight-path angle respectively, L , D and T are the lift force, resistance and side force respectively, and q is the rate of fuel consumption per unit time at the height h .

The climb trajectory can be divided into several parts according to the equal height Δh. Assume the UAV flies from point h_i to point h_{i+1}, the change of airspeed and the path tilt angle are: $v_i \to v_{i+1}$, $\gamma_i \to \gamma_{i+1}$. Δt_i, $\Delta x_i, \Delta W_{f_i}$ are the flight time, horizontal displacement and the fuel consumption respectively:

$$\Delta t_i = \frac{m(v_{i+1} - v_i)}{T \cos \alpha_i - L \sin \alpha_i - D - mg \sin \gamma_i} \tag{5}$$

$$\Delta x_i = \frac{1}{2}(v_i + v_{i+1}) \Delta t_i \cos \gamma_i \tag{6}$$

$$\Delta W_{f_i} = \frac{1}{2}(q_{h_i} + q_{h_{i+1}}) \Delta t_i \tag{7}$$

c_t and c_f are the flight cost weight of the time and the fuel consumption, and the flight cost of the climbing trajectory is:

$$J_i = c_t \Delta t_i + c_f W_{f_i} \tag{8}$$

Because the value of the angle of attack is small (usually less than 10°) , so the equation (5) can be simplified as:

$$\Delta t_i = \frac{m(v_{i+1} - v_i)}{T_i - D_i - mg \sin \gamma_i} \tag{9}$$

So the time cost t of the climbing trajectory, the total horizontal voyage x, and the total fuel consumption W are be expressed respectively as:

$$t = \sum_{i=1}^{n} \Delta t_i ,\ x = \sum_{i=1}^{n} \Delta x_i ,\ W_f = \sum_{i=1}^{n} \Delta W_{f_i} \tag{10}$$

The minimum value of J in equation (10) can be used as the optimization performance index:

$$J = \min \sum_{i=1}^{n} J_i \tag{11}$$

3 Optimization of the Climbing Trajectory Based on the IPSO

3.1 Improvement of the PSO

In the PSO, every member of the swarm, namely particle flies in the multi-dimensional search space at a certain speed, and keeps updating the information of its own position and velocity based on its own inertia, experience and social experience.

The dimension of the particle swarm is the dimension of the search space; each dimension represents a parameter which is preparative optimized.

Assuming the number of the search space's dimension is n, the position and the velocity of particle i at time t can be expressed as[5]:

$$X_i(t) = [x_{i1}(t), \ldots x_{ij}(t), x_{i,j+1}(t), \ldots x_{in}(t)] \tag{12}$$

$$V_i(t) = [v_{i1}(t), \ldots v_{ij}(t), v_{i,j+1}(t), \ldots v_{in}(t)] \tag{13}$$

The exon j dimension position updating formula of particle i at time $t+1$ is:

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \tag{14}$$

In the PSO, y_i is used to record the optimal search position of the particle i, and the jth dimension velocity updating formula of particle i can be expressed as:

$$v_{ij}(t+1) = v_{ij}(t) + c_1 r_{1j}(t)[y_{ij}(t) - x_{ij}(t)] + c_2 r_{2j}(t)[\hat{y}_j(t) - x_{ij}(t)] \tag{15}$$

In the equation (15), c_1 and c_2 are the accelerating constant of the cognitive portion and the social portion respectively, they are also optional parameter; r_{1j} and r_{2j} are the random number of interval [0,1], which satisfies uniform distribution.

To ensure the PSO has a good convergence, the inertial weight w can be introduced to improve the PSO, then the equation (14) can be changed to:

$$v_{ij}(t+1) = w v_{ij}(t) + c_1 r_{1j}(t)[y_{ij}(t) - x_{ij}(t)] + c_2 r_{2j}(t)[\hat{y}(t) - x_{ij}(t)] \tag{16}$$

To ensure the algorithm have good convergence and strong exploration ability, the dynamic method of linear reduction is used to set w, and the changing formula is[6]:

$$w(t) = (w(0) - w(n_t))\frac{(n_t - t)}{n_t} + w(n_t) \tag{17}$$

In the equation (17), n_t is the maximum step of the algorithm execution iteration time, $w(0)$ is the final inertial weight (the value of it is small), $w(t)$ is the weight at time t, and $w(0) > w(n_t)$.

The flow chart of the IPSO is as follows:

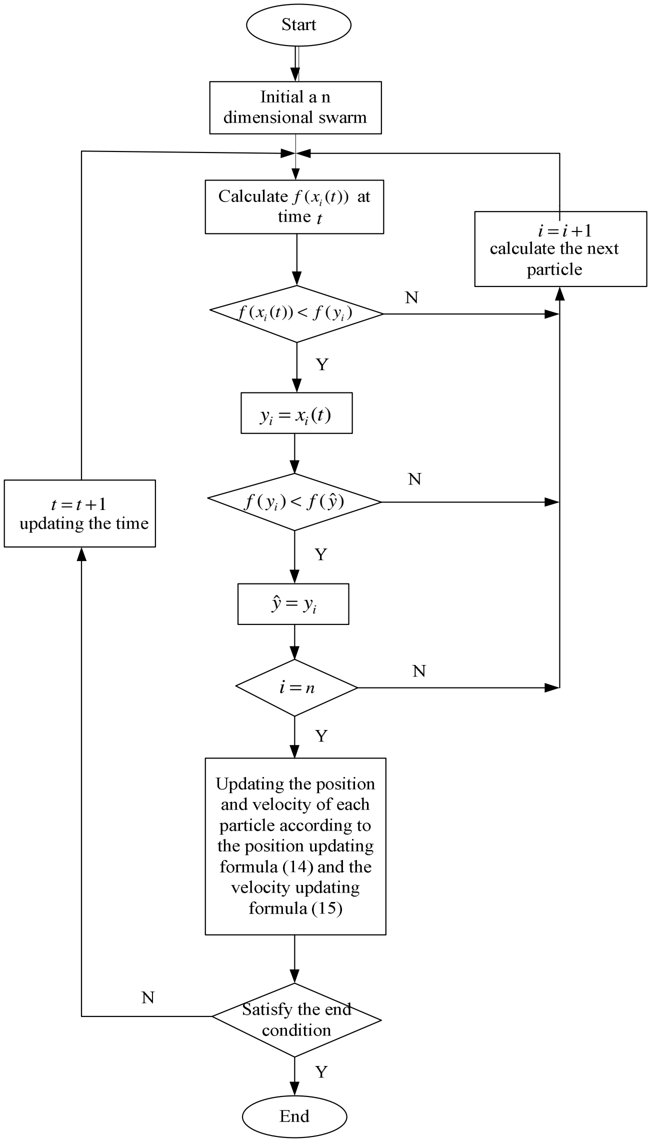

Fig. 1. Flow Chart of the IPSO

3.2 Climbing Trajectory Optimization Based on IPSO

If the global optimization is made to the entire climbing trajectory, the whole optimization parameters of the entire height will be included; this may lead to the dimension of the particle swarm become too large. For example, if the number of preparative optimization parameters is m, and the entire height is divided into n parts, then the number of preparative optimization parameters in the entire climbing trajectory is $m*n$,it is also the dimension of the particle swarm. If the dimension of the particle swarm is too large, it will increase the complexity of the algorithm, decrease the search speed, and even not find the optimal solution.

In this paper, the parameter is optimized in each part, so the dimension of the particle swarm is m, the dimension of the particle swarm is greatly reduced from $m*n$ to m .The optimization problem of the climbing trajectory should be converted into the optimization problem of the equation (18):

$$J = \min \sum_{i=1}^{n} J_i \approx \sum_{i=1}^{n} (\min J_i) \tag{18}$$

In order to make the UAV climb to the target height as soon as possible, the maximum thrust climbing method is used in this research, the specific steps of the optimization algorithm is as follows:

(1) The initial speed is known, aiming at the first part (h_0, h_1), the initial speed v_1 in the next part (h_1, h_2) can be obtained by optimizing the value of (v_1, γ_0);

(2) Δx_0 and ΔW_{f_0} can be obtained according to equation (6) and (7), then the comprehensive cost J_0 in the first part (h_0, h_1) can be calculated by equation (18);

(3) To every part (h_i, h_{i+1}), repeat step (1);

(4) Repeat step (2), the optimal climbing trajectory can be obtained by optimizing and synthesizing every part of height.

4 Simulation and Analysis

The proposed method is used in a certain type of UAV to optimize its climbing trajectory. The UAV climbs from $1000\,m$ to $10000\,m$ at the initial speed of $0.4\,Ma$, and the constraint conditions are:

$$\begin{cases} 0.4 \le Ma \le 0.7 \\ 0^\circ \le \alpha \le 10^\circ \\ 0^\circ \le \theta \le 11^\circ \end{cases}$$

The optimization step chosen in this paper is $\Delta h = 500m$, and the optimization results are shown in Fig.2 and Fig.3:

Compared with the high altitude, the fuel consumption is higher in the low altitude, so the climbing rate in the low altitude should grow quickly, and climb at the high flight-path angle so that the UAV can deorbits the low altitude area which has higher fuel consumption. As shown in the Fig.2, the climb rate is highest in the

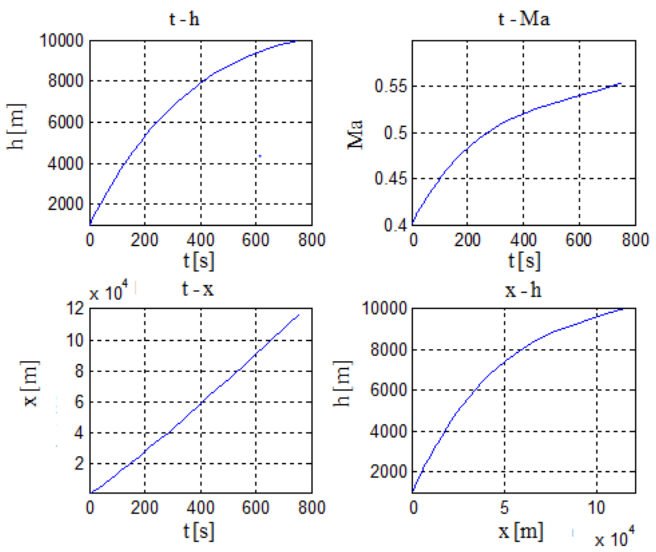

Fig. 2. The Simulation Results of Climbing Trajectory Based on IPSO

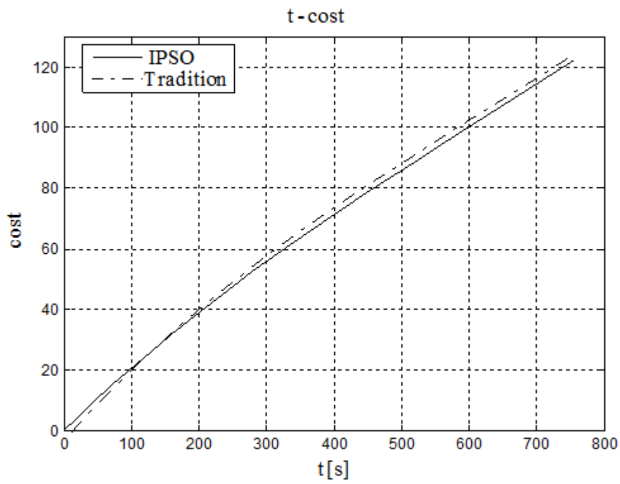

Fig. 3. Comparison of Climbing Trajectory Cost by Using the IPSO and the Traditional Algorithm

low altitude, and decreases gradually with the height increasing; The climb rate decreases quickly when the UAV reaches a certain height in order to determine the optimal climbing trajectory according to the performance index. The analysis conclusions verify the reliability of the results and the feasibility of the research method.

As shown in the Fig.3, at the beginning in climbing, the cost of IPSO is slightly larger than the cost of the traditional algorithm; After 200s, the cost of IPSO is smaller than the cost of the traditional algorithm. As a whole, the cost of IPSO is smaller than the cost of the traditional algorithm about 2.3%.

5 Conclusion

In this paper, the IPSO is researched to solve the optimization problem of the UAV's climbing trajectory, the time cost and fuel consumption are considered synthetically. The operation cost of the UAV's climbing trajectory is saved to a certain degree, and the climbing speed is also increased. The reliability and superiority of the IPSO is verified by example calculation.

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