Three-Dimensional Planning of Arrival and Departure Route Network Based on Improved Ant-Colony Algorithm

Wang Chao(王超)*, *He Chaonan*(贺超男)

College of Air Traffic Management, Civil Aviation University of China, Tianjin 300300, P. R. China

(Received 18 April 2014; revised 2 May 2015; accepted 12 July 2015)

Abstract: In order to improve safety, economy efficiency and design automation degree of air route in terminal airspace, Three-dimensional(3D) planning of routes network is investigated. A waypoint probability search method is proposed to optimize individual flight path. Through updating horizontal pheromones by negative feedback factors, an antcolony algorithm of path searching in 3D terminal airspace is implemented. The principle of optimization sequence of arrival and departure routes is analyzed. Each route is optimized successively, and the overall optimization of the whole route network is finally achieved. A case study shows that it takes about 63 s to optimize 8 arrival and departure routes, and the operation efficiency can be significantly improved with desirable safety and economy.

Key words: terminal airspace; arrival/departure route; ant-colony algorithm; path planning; transportation network design

CLC number: V355.1 **Document code**: A **Article ID**: 1005-1120(2015)06-0654-11

0 Introduction

Arrival and departure route network are important airspace resources and play an important role in terminal air traffic control. Well structured route network can not only reduce flight conflicts but also shorten flight distances, thus improving safety margin and reducing aircraft operating cost. However, artificial design of arrival/departure routes has been subject to limited signal covering ranges of ground-based navigation equipments in the past, and could not efficiently balance safety with economy. Fortunately, the application of performance based navigation (PBN) technology provides a technical basis for flexible route planning. Therefore, it is valuable to study automatic arrival/departure route planning for satisfying multiple objective requirements.

Arrival and departure routes in terminal airspace is a tree network composed of one-way paths in three-dimensional (3D) space. Arrival and departure routes regulate landing aircraft and taking-off aircraft seperately, which is a kind of traffic flow segregation. In arrival/departure route planning, it is the priority to search the proper flight path between two points, while the connectivity between different routes can be neglected. Obviously, arrival/departure route network planning is different from common network design problem (NDP), and similar to the thought of "routing one by one and further optimizing them into a network"[1-3] in public traffic network. Therefore, the flight path planning in 3D airspace can be considered as the foundation of arrival/departure route planning.

At present, abundant researches have focused on path planning including real-time trajectory planning of air launched cruise missile[4], UAV threat avoidance path planning[5-6], and path planning of mobile robot in dynamic environment[7-8]. Path planning methods can be roughly classified into three categories: (1) Path planning based on schematic diagram; (2) path planning based on grid; (3) path planning based on analo-

* **Corresponding author**: Wang Chao, Associate Professor, E-mail: wangch6972@aliyun.com.

How to cite this article: Wang Chao, He Chaonan. Three-dimensional planning of arrival and departure route network based on improved ant-colony algorithm[J]. Trans. Nanjing U. Aero. Astro., 2015,32(6):654-664.
http://dx.doi.org/10.16356/j.1005-1120.2015.06.654

gy. Each kind of methods utilizes a different heuristic algorithm, such as Voronoi diagram, particle swarm algorithm, A^* algorithm, genetic algorithm, and artificial neural network, to search the optimal path satisfying certain conditions.

However, the previous work mainly concentrated on 2D space path planning, while 3D arrival/ departure route network has been seldom reported. Pfeil[9] has proposed a 3D optimization method of arrival/departure routes based on A^* algorithm, but its search space was so large that the running time would extend exponentially with an increasing number of routes to be optimized.

In our work, the optimization of individual route is achieved first, and then a probability search method is proposed to select waypoints. Therefore, the path search algorithm in 3D space is established with the help of ant-colony algorithm. On this basis, the previous optimization results are used as current constraints according to a certain priority principle, and the arrival/departure routes are planed one by one to complete the planning and design of route network. Finally, the runway 05L of Xi′an/Xianyang Airport is taken as an example for the verification and analysis of our proposed algorithm.

1 Design of Arrival/Departure Route Network in Terminal Airspace

The arrival/departure route in terminal airspace is referred to an airborne route provided by ground-based or satellite-based navigation equipment which meets the requirement of a certain navigation performance. Arrival aircraft converge to runway-in-use along the arrival route from entrance waypoints of different upper air routes (UARs), and eventually finish descending and landing; while departure aircraft take-off from runway-in-use and diverge to different exit waypoints connected with the UARs, and eventually reach cruising level. Therefore, the arrival/departure routes and the network composed by them are important facilities for controlling air traffic. Regarding to the principle of ″routing one by one and further optimizing them into a network″, the network planning of arrival/departure route mainly includes two challenges:

(1) Search the optimal route in 3D airspace which meets the requirement of flyability with a pair of known original waypoint and destination waypoint of an individual route;

(2) Sequentially optimize the whole network of multiple paths based on the optimization of individual routes.

1.1 Model of initial conditions for terminal airspace

Terminal airspace is the space scope of arrival/departure route network optimization, and the establishment of terminal airspace diagram model is the precondition of arrival/departure route network research.

A model of initial conditions of general airspace is established, as shown in Fig. 1. With the reference point of airport as the coordinate origin O, a rectangular plane coordinate system is constructed, and thus the main units of terminal airspace include:

(1) Terminal control area G

The boundary of control zone G is defined by a point sequence $\{v_1, v_2, v_i, \cdots, v_z\}$, which also determines the space scope of arrival/departure route network.

(2) Restricted airspace (RA)

RA refers to the non-civil airspace, usually denoted by a convex polygon. Considering RA spatial attributes, we put forward four kinds of RA models: Ground restricted area, suspended restricted area, tall restricted area and final approach restricted zone, where the final approach restricted zone is a populated area of landing aircraft. In order to prohibit the routes traversing from final approach and avoid route crossing, a rectangular restricted area is designated, with a width of 20 km where the runway center is the starting point, and with a length of 30 km along the inverse landing direction.

(3) Runway (RW) and original and destina-

tion points of routes

RW is described by the airport reference point c_r, the runway length l and the runway number n_r denoting its orientation. The starting point a_{si} of an arrival route R_{arr} is the transfer point between UAR and terminal airspace; and the terminal point is the initial approach fix a_{ei} of runway-in-use; the starting point of a departure route R_{dep} is the initial turning point d_{si} in taking-off direction, and the exit point is the transfer point d_{ei} of terminal airspace and UAR.

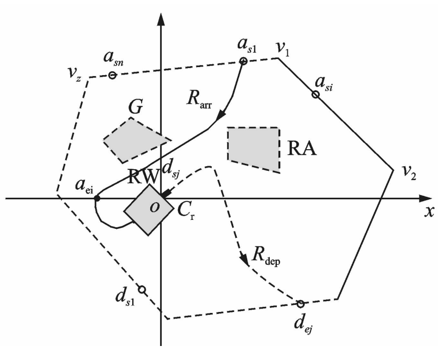


Fig. 1 Initial conditions model in terminal airspace

1.2 Route planning

Network planning of arrival /departure route is essentially to search 3D paths which obey the constraint of avoiding all kinds of restricted areas and meet certain optimization objectives in the terminal airspace. Suppose route R has m segments, with starting point $p_0 = (x_s, y_s, h_s)$ and ending point $p_e = (x_e, y_e, h_e)$, where x_s, y_s, h_s and x_e, y_e, h_e are the lateral, the longitudinal and the vertical coordinates of p_0 and p_e, respectively. Usually route R can be expressed by a waypoint sequence or a segment sequence. Here, segment is a vector composed of the current waypoint $p_i = (x_i, y_i, h_i)$ and the next waypoint $p_{i+1} = (x_{i+1}, y_{i+1}, h_{i+1})$, where x_i, y_i, h_i represent the lateral, the longitudinal and the vertical coordinates, respectively.

2 Multiple Objective Model of Arrival/Departure Route Planning

The solution space range of arrival/departure route planning would be quite large[9], causing a low algorithm efficiency, if feasible waypoints was directly searched in 3D space. Therefore, we expect to decouple the optimization of 3D routes into 2D(horizontal and vertical) planes. Route optimization in horizontal plane mainly solves the shortest path problem, while the vertical one mainly tries to approach the most economical performance profile of aircraft. The above problems have different objective dimensions, large numerical difference and incommensurability, so it is necessary to establish a fuzzy satisfaction function for each objective.

2.1 Objective functions

(1) Economy in horizontal profile

Total length of a route is the main factor that affects the horizontal profile economy of arrival/departure route. By projecting each segment $\boldsymbol{S}_i = p_i p_{i+1}$ of route R to the horizontal plane, we can obtain the corresponding length $d_i = |p'_i p'_{i+1}|$. Defining d as the total length of projection, then we can get

$$d = \sum_{i=1}^{m} d_i \tag{1}$$

In order to ensure the economical operation of the route, $d_{\min}$ is defined as the shortest straight distance between the starting point and the ending point of route R, without considering the restricted airspace condition. Selecting $d_{\min}$ as a reference of route projection length, then $d_{\min}$ can be calculated as follows

$$d_{\min} = \sqrt{(x_e - x_s)^2 + (y_e - y_s)^2} \tag{2}$$

In order to evaluate the satisfaction degree of horizontal profile economy and ensure the total length of the route projection d approaches $d_{\min}$ as close as possible, the economical membership function of route R in the horizontal profile is established as

$$\mu_{\widetilde{H}}(R) = \begin{cases} 1 & d = d_{\min} \\ 2 - \dfrac{d}{d_{\min}} & d_{\min} < d \leqslant 2d_{\min} \\ 0 & \text{Other} \end{cases} \tag{3}$$

(2) Closeness of flight performance in vertical profile

In vertical profile, statistical analysis showed that the optimal climbing model was to climb to cruise altitude as soon as possible with 7% gradient, while the optimal descending model selected

3% gradient[10]. In order to meet the requirements of aircraft flight performance and obtain the optimal economical profile, route gradient should approach the optimal vertical section as close as possible.

Suppose that climb/descent gradient of segment $\boldsymbol{S}_i$ of route R is γ_i , which obeys Gauss distribution before aircraft climb to h_1 or descend to h_2. Thus, the approaching degree membership function of segment $\boldsymbol{S}_i$ in the vertical section can be expressed as

$$\mu_{\tilde{v}_I}(\gamma_i)=\begin{cases} e^{-\left(\frac{|\gamma_i-\gamma_0|}{\sigma}\right)^2} & (h<h_1)\vee(h<h_2) \\ 1 & \gamma_i=\gamma_0 \\ 0 & (h\geqslant h_1)\vee(h\geqslant h_2) \end{cases} \tag{4}$$

where γ_0 denotes the optimal climb/descent gradient, σ the extent of deviation between γ_i and the corresponding optimal climb/descent gradient, h the section climb/descent height, and h_1 and h_2 represent the highest route climb and descent point, respectively.

As the entire route is formed by multiple segments, the approaching degree of route R in the vertical profile equals to the sum of approaching degree in each segment, as

$$f_V(R)=\sum_{i=1}^{m}\mu_{\tilde{V}_i}(\gamma_i) \tag{5}$$

To unify the dimension of different objectives, all the vertical profile functions should be normalized before next operation. Define $f_{\max}$ as the sum of optimal gradient in each segment of route R, and then the membership functions of the whole route R in the vertical profile can be expressed as

$$\mu_{\tilde{V}}(R)=\begin{cases} 1 & f_V(R)=f_{\max} \\ 1-\dfrac{f_{\max}-f_V(R)}{f_{\max}} & 0<f_V(R)\leqslant f_{\max} \\ 0 & f_V(R)\leqslant 0 \end{cases} \tag{6}$$

2.2 Constraint conditions

(1) Segment obstacle safety

Segment obstacle means that the civil aircraft need to maintain a sufficient vertical distance when they fly over each ground restricted zone. Suppose that the aircraft flight height is h and the minimum obstacle clearance of current flight step is minimum obstacle clearance (MOC). The restricted area in terminal airspace is $B=\{b_1,b_2,\cdots,b_j,b_g\}$, where $b_j=(x_j,y_j,h_j)$, with x_j,y_j and h_j denoting the lateral, the longitudinal and the relative height, respectively. The starting point of segment $\boldsymbol{S}_i$ is $p_i=(x_i,y_i,h_i)$, and the ending point is $p_{i+1}=(x_{i+1},y_{i+1},h_{i+1})$.

According to the requirements of DOC8168[11], a horizontal protection zone with a width of w and a length of $|s_i|$ is constructed by taking the projected trajectory $|s_i|$ of $\boldsymbol{S}_i$ as center. If obstacle b_j is in the protection zone, the obstacle should be considered as a potential dangerous obstacle. Then, it is necessary to calculate the vertical obstacle clearance h_{MOC}[12], as

$$h_{\text{MOC}}=\begin{cases} \text{MOC} & |y|<\dfrac{w}{4} \\ \text{MOC}\times\left(\dfrac{2w-4y}{w}\right) & \dfrac{w}{4}<|y|<\dfrac{w}{2} \end{cases} \tag{7}$$

where y is the distance between obstacle b_j and the projected trajectory measured along the direction perpendicular to the trajectory. Therefore, the vertical distance between $\boldsymbol{S}_i$ and b_j should meet the following conditions

$$\begin{cases} h_s=h_b-h_j \\ h_s\geqslant h_{\text{MOC}} \end{cases} \tag{8}$$

(2) Obstacle avoidance

The tall restricted area in terminal airspace is impassable obstacle for civil aircraft. Therefore, the designed routes must avoid this kind of restricted area and maintain a sufficient horizontal distance d_0. Notably, it is necessary to calculate the distances between each segment and the tall restricted area when compute the distance between the route and the tall restricted area. Suppose the vertex sequence of a restricted area lines in a clockwise order as $o_1,o_2,\cdots o_k,\cdots,o_K$; the segment of route R is $\boldsymbol{S}_i=(p_i,p_{i+1})$, and that the vertical intersection point of o_k and $\boldsymbol{S}_i$ or its extension line is p_{ik}. Define $\boldsymbol{q}=(p_i,p_{ik})$, $\boldsymbol{d}_1=(o_k,p_i)$, $\boldsymbol{d}_2=(o_k,p_{i+1})$ and $\boldsymbol{d}_{\text{p}}=(o_k,p_{ik})$, and thus the horizontal distance between vertex o_k and $\boldsymbol{S}_i$ is[13]

$$d_{s_{ij}}=\begin{cases}|\boldsymbol{d}_1| & \boldsymbol{S}_i\cdot\boldsymbol{q}<0\\ |\boldsymbol{d}_\mathrm{p}| & (\boldsymbol{S}_i\cdot\boldsymbol{q}>0)\wedge(0\leqslant|\boldsymbol{q}|\leqslant\boldsymbol{S}_i)\\ |\boldsymbol{d}_2| & (\boldsymbol{S}_i\cdot\boldsymbol{q}>0)\wedge(|\boldsymbol{q}|>\boldsymbol{S}_i)\end{cases} \tag{9}$$

For all the distances between the segment and the tall restricted area, take the minimum value as the distance between route R and the tall restricted area[13], namely

$$D(R,R_\mathrm{RA})=\min\{\min(d_{ik})\}$$
$$i=1,2,\cdots,m;\ j=1,2,\cdots,K \tag{10}$$

where R_RA is the using airspace of restricted area, m the arrival/departure route segment number, and K the number of tall restricted zone vertices.

Therefore, the following condition needs to be satisfied for route R to bypass the tall restricted area horizontally

$$D(R,R_\mathrm{RA})\geqslant d_0 \tag{11}$$

(3) Flight feasibility constraint

Flight feasibility is an index of the air route smoothness degree. In order to meet the requirements of mobility and passenger comfort of civil aircraft, the deflection angle between a segment and the next segment should satisfy

$$\frac{\pi}{2}\leqslant\theta\leqslant\frac{3\pi}{2} \tag{12}$$

In the planning set of arrival and departure routes, the objectives corresponding to each solution has its own membership function value, and we can determine the satisfaction degree of the planning according to the relative distance. Considering different objective requirements, we adopt the optimization strategy of weighted sum to realize the maximum optimization of each objective under the following constraint conditions

$$\text{s. t.}\begin{cases}\max(\omega_1\mu_{\tilde{H}}(R)+\omega_2\mu_{\tilde{V}}(R))\\ \text{Eq. (8)}\\ \text{Eq. (11)}\\ \text{Eq. (12)}\\ \omega_1+\omega_2=1\end{cases} \tag{13}$$

3 Route Planning Based on Improved Ant-Colony Algorithm

3.1 Initial solution based on the MAKLINK line

According to the research of Maki K[14], path planning method based on visual diagram can effectively avoid the restricted area and reduce the search space of waypoint, thus improving the algorithm efficiency. Therefore, the MAKLINK line should be designated based on the restricted zones in terminal airspace, e. i., o_1 o_2 o_3 o_4. In the route optimization process, arrival and departure routes are not allowed to exceed the internal region of the terminal airspace, so the MAKLINK line should be removed out of the terminal airspace, as the dotted line in Fig. 2.

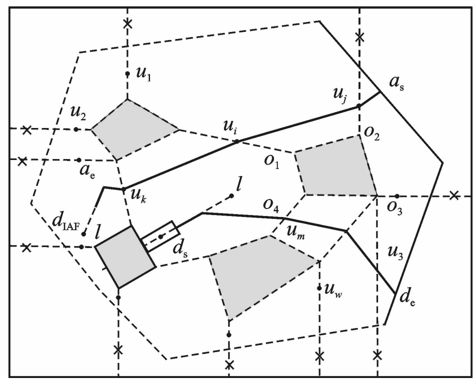


Fig. 2 Initial solution of route planning

As shown in Fig. 2, d_IAF is the initial approach location of approach procedure. d_s indicates the starting point and d_e the end of a departure route. We denote a_s as the starting point and a_e the end of arrival route. The midpoint of every MAKLINK line is denoted as u_i. When departing or arriving, turning angels of aircraft should meet the requirement of flight feasibility. Therefore we need to take the route deflection angle as the flight feasibility constrain. We select d_s or d_IAF as starting points, MARKLINK lines l_1 and l_2 are artificially constructed separately. Normally they are 30 km long. Thus, the defection angle can be satisfied by choosing points on them.

The initial solution of route is a feasible route R_0 in the solution space composed of midpoints of MAKLINK lines, the given starting point and the ending point of each arrival/departure route, as follows:

Given a starting point and an ending point of each arrival/departure route, an initial solution R_0 could be searched in the solution space composed of midpoints of MAKLINK lines using Dijkstra algorithm[15], and R_0 can be expressed as

$$R_0=(a_\mathrm{s},\ u_j,\ \cdots,u_i,\cdots,u_k,a_\mathrm{e})\ \text{or}$$

$$R_0 = (d_s, u_m, \cdots, u_w, \cdots, u_3, d_e) \qquad (14)$$

To sum up, route R_0 is the optimized initial feasible solution of arrival/departure route, and the point set sequence in MAKLINK lines makes up of the route solution space.

3.2 3D space route optimization based on improved ant colony algorithm

Ant-colony algorithm (ACO) is a new heuristic algorithm based on evolution simulation, which can be used to solve complex optimization problems[16]. The goal of arrival/departure route optimization is to make the vertical profile close to the optimal section on the premise of the shortest total length of the route in horizontal plane. Therefore, a waypoint searching method which works along the horizontal direction first and then the vertical direction is proposed.

3.2.1 Searching rules of horizontal and vertical waypoints

Fig. 3 shows the searching rules of segments. Suppose x ants line from the starting point p_0 to the ending point p_e. At waypoint $p_i = (x_i, y_i, z_i)$, the searching steps of the next waypoint p_{i+1} are as follows:

(1) Divide the searching solution space of waypoint into two parts as horizontal and vertical sections, and partition the MAKLINK line $L_iL_{i'}$ equally in the horizontal section, with the level discrete degree of a and discrete nodes of $l_1, l_2, \cdots, l_a$;

(2) Select horizontal node l_i with a certain probability p_{hoz}, as calculated in Eq. (15);

(3) On this basis, partition the gradient equally, with the vertical discrete degree of b and discrete nodes of $e_1, e_2, \cdots, e_b$;

(4) Select vertical node e_j according to a certain probability p_{ver}, as calculated in Eq. (15)

$$\begin{cases} p_{\text{hoz}} = \dfrac{\tau_{L_i}^{\alpha} \eta_{L_{i'}}^{\beta}}{\sum\limits_{z \in L_i L_{i'}} \tau_{l_z}^{\alpha} \eta_{l_z}^{\beta}} \\ p_{\text{ver}} = \dfrac{\tau_{e_j}^{\alpha} \eta_{e_j}^{\beta}}{\sum\limits_{w \in E_j E_{j'}} \tau_{e_w}^{\alpha} \eta_{e_w}^{\beta}} \end{cases} \qquad (15)$$

where $\tau_{L_i}^{\alpha}$ and $\tau_{e_j}^{\alpha}$ denote the pheromones in horizontal and vertical directions, respectively, $\eta_{L_i}^{\beta}$ and $\eta_{e_j}^{\beta}$ the node heuristic values in horizontal and vertical directions, respectively, α is the phero-mone importance factor, and β the node heuristic value.

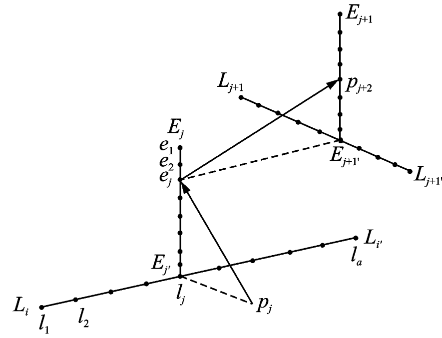


Fig. 3 Searching rules of segments

Through the above steps, the new waypoint can be obtained, and the waypoint search of the whole route can be achieved by repeating these steps.

3.2.2 Updating rules of horizontal and vertical pheromones

In the ant-colony algorithm, as a media of information transmission, pheromones are to guide the algorithm running orientation. In general, the positive feedback updating rule is adopted, namely the more ants walk along a path, the higher the probability of later ants choosing that pathis. However, if the waypoints do not satisfy the constraints of obstacle safety and flight feasibility, the algorithm will choose not to update pheromones or to abandon the route, which leads to local optimal or no optimal solution for the route search, as well as a slow convergence of the algorithm. Therefore, the negative feedback rule is proposed to update such pheromones.

Suppose f_0 is an evaluation value of the previous route. If the new route $f(R)$ satisfies the constraints and excels the former route, the pheromones τ_{hoz} in the horizontal direction and τ_{ver} in the vertical direction are updated according to the positive feedback rules. If $f(R)$ does not satisfy the constraints, it is necessary to add negative feedback factor r_e into pheromones of the new route to reduce the pheromones in the horizontal direction and further enlighten the route to fly around horizontally

$$\tau_{\text{hoz}} = \begin{cases} (1-\rho)\tau_{\text{hoz}} + \rho\tau_0 & f(R) \leqslant f_0 \\ (1-\rho)\tau_{\text{hoz}} + \rho(\tau_0 \cdot r_e) & f(R) = 0 \end{cases} \tag{16}$$

$$\tau_{\text{ver}} = (1\text{-}\rho)\tau_{\text{ver}} + \rho\tau_0 \tag{17}$$

where τ_0 is the initial value of pheromones, ρ the evaporation factor of pheromones ($0<\rho<1$), and r_e the pheromone decreasing constant, which is inversely proportional to the shortest length of the route D, namely $r_e = \frac{1}{kD}$ (k is a constant number).

4 Optimization of Arrival/ Departure Route Network

4.1 Principles of optimization sequence

There are usually many arrival/departure routes in terminal airspace, which inevitably cross with each other. As the optimization order directly affects economic benefits, principles for optimization should be proposed:

(1) Since civil aircraft cost more fuel in low altitude flying and climbing than in high altitude cruising, departing aircraft need to climb up to cruising altitude under high thrust without interruption. On the other hand, arriving aircraft generally use descent mode of engine idling with almost zero thrust, and the fuel consumption is little. Thus, route length is no longer a bottleneck of reducing fuel consumption especially in continuous descent approach(CDA) technology. Therefore, the principle that departure route is prior to arrival route is proposed.

(2) On the basis of the first principle, lots of aircraft can operate closely to their ideal vertical profile by reducing interference to the vertical profile of the routes with heavy traffic flow, which decreases the overall cost of fuel. Therefore, interference minimization of those routes with heavier traffic flow is a prior factor in route optimization.

4.2 Vertical separation of route intersection

Route intersection problem is an inherent factor which leads to flight conflicts, so enough vertical separation should be established as far as possible at the intersection. Suppose that arrival route R_{arr} and departure route R_{dep} have an intersection z in the horizontal plane belonging to segments $p_i\, p_{i+1}$ and $q_j q_{j+1}$, and that the gradients are γ_a and γ_d respectively. If $p_i = (x_a, y_a, h_a)$ and $q_j = (x_d, y_d, h_d)$, we define d_{arr} and d_{dep} as the horizontal distances between the segment starting points p_i, q_j and the intersection, respectively, and the vertical separation at the intersection can be obtained as

$$d_z = | h_a + d_{\text{arr}} \cdot \gamma_a - h_d + d_{\text{dep}} \cdot \gamma_d | \tag{18}$$

In order to satisfy the flight safety margin at the intersection, we take the designed departure route R_{dep} as a vacant restricted area, and construct a rectangular protection zone of 300 m wide and $|q_j q_{j+1}|$ long with segment $q_j q_{j+1}$ as the center. If $p_{\text{i}+1}$ is in the zone, the intersection does not meet the requirement that the vertical separation between arriving and departing aircraft should be larger than 300 m, and we should search waypoint again according to Section 4.3 until the vertical separation satisfies the requirement.

4.3 Lateral separation between routes

To ensure the proximity of two adjacent routes with adequate lateral safety distance, the distance between routes needs to be determined. We separate the two routes with seperate unit length separation d_a, and obtain the discrete point sequence that characterizes the routes. As a result, the distance between the two routes can be calculated using the distance between two point sets of different routes. We adopt forward Hausdorff distance to define the distance of two flight paths as

$$d(R_i, R_j) = \max_{p_{(i,s)} \in R_i} \min_{p_{(j,t)} \in R_j} \| p_{(i,s)} - p_{(j,t)} \| \tag{19}$$

where $p_{(i,s)}$ and $p_{(j,t)}$ denote the discrete point coordinates with sequence number s and t, respectively. Therefore, the lateral separation should be larger than 10 000 m in order to ensure the lateral safety margin between routes.

4.4 Route evaluation function

Route evaluation function is a function to assess the satisfaction degree of routes, which calculates the quantitative evaluation value according to the route economy in the horizontal section and the approaching degree in the vertical section. We build a piecewise route evaluation function under route constraints to describe the feasibility of objective function in the horizontal and vertical sections. Route evaluation function is defined as

$$f(R)=\begin{cases}\omega_1\mu_{\tilde{H}}(R)+\omega_2\mu_{\tilde{V}}(R) & (h_s\geqslant h_{\mathrm{MOC}})\wedge(D(R,R_{\mathrm{RA}})\geqslant d_0)\wedge(\frac{3\pi}{2}\geqslant\theta\geqslant\frac{\pi}{2})\wedge \\ & (d_z\geqslant 300)\wedge(d(R_i,R_j)\geqslant 10\ 000) \\ 0 & \text{Other}\end{cases} \tag{20}$$

where ω_1 and ω_2 are the weighting factors to evaluate different objectives.

5 Case Study

Taking the 05L runway of Xi′an/Xianyang international airport as an example, the 3D planning of arrival/departure route network is studied, and the initial condition diagram model in terminal airspace is shown in Fig. 4. The terrain of this terminal airspace is complex and there are many ground restricted zones. Considering four typical dangerous obstacles in Fig. 4, obstacle b_1 is 1 359 m high, and four tall restricted zones are R306, R307, R308, and R309. Besides, a final approach restricted zone R310 of 20 km wide and 30 km long is designated with the runway center as its starting point. Select the end of Runway 05L as the starting point TOF, while the compulsory reporting points of TEBIB, LOVRA and P54 and the requested reporting point of P32 as the ending points, and then we can define four departure routes of $R_{\mathrm{d1}}, R_{\mathrm{d2}}, R_{\mathrm{d3}}, R_{\mathrm{d4}}$. Select the compulsory reporting points NUGLA and VOR navigation stations of NSH and HO as starting points, while the initial approaching locating point IAF as an ending point, and we can define three arrival routes of $R_{\mathrm{a1}}, R_{\mathrm{a2}}, R_{\mathrm{a3}}$. The MAKLINK line generated according to Section 3.1 is a dotted line as shown in Fig. 4.

(1) Individual route planning based on ant colony algorithm

Take the departure route R_{d1} as an example. The initial solution of the route is constructed according to Section 3.1, as shown by a dotted line

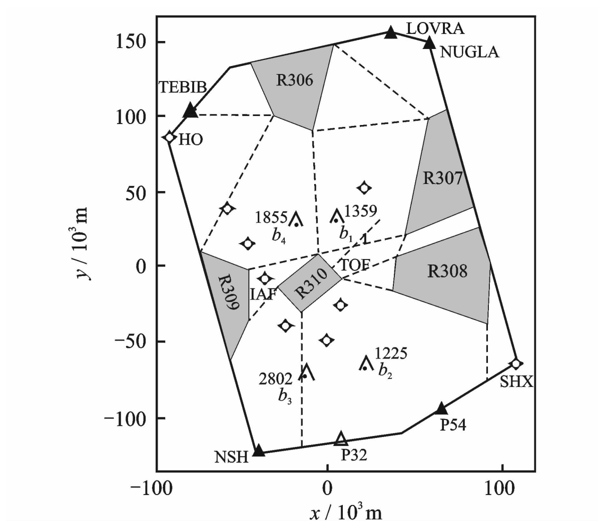


Fig. 4 Terminal airspace model of Xi′an/Xian Yang Airport

in Fig. 5(a). Select the horizontal dispersion as $a=15$, the vertical dispersion as $b=10$, number of ants as $x=20$, number of iterations as Iteration $=500$, pheromone initial value as $\tau_0=0.000\ 1$, and pheromone evaporation factor as $\rho=0.5$. Since the variation of total length is an important factor affecting the operation cost of the route, this objective will be preferentially considered when optimizing routes. Set the weighting factor $\omega_1=0.6$ and $\omega_2=0.4$, and the initial route can be optimized without considering obstacle constraints by an improved ant-colony algorithm, which is shown as the solid line in Fig 5. According to Eqs. (7,8) where $h_{\mathrm{MOC}}=162$ m and $h_s=137$ m, b_4 is determined as a dangerous ground obstacle. At this moment, we can introduce the negative feedback factor $r_e=\dfrac{1}{4\ 500D}$, and use Eq. (16) to reduce pheromones of waypoint in the horizontal direction, finally enlightening the route

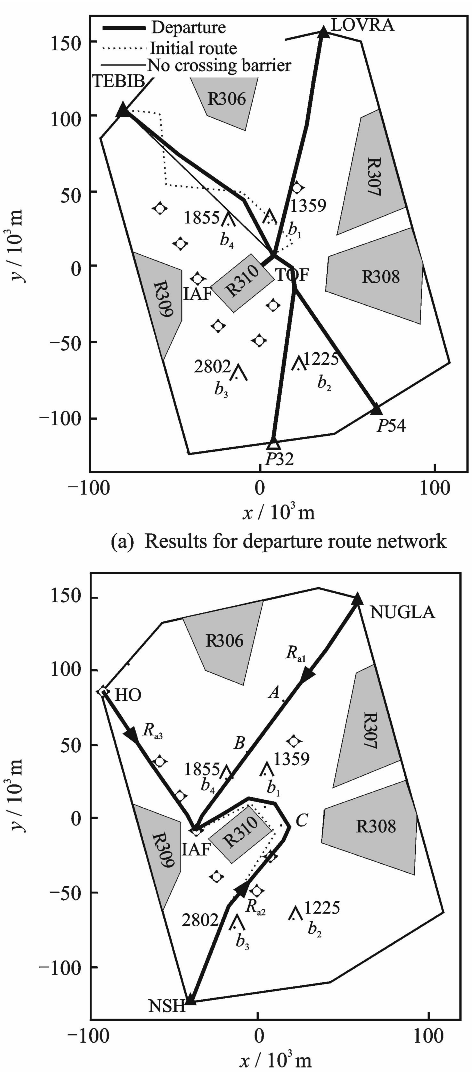
Table 1 Optimization results of air route R_{d1}

Parameter	Seg1			Seg2			Seg3			Seg4			$\mu_{\tilde{H}}(R)$	$\mu_{\tilde{V}}(R)$
	d/m	γ_i/%	θ/(°)	d/m	γ_i/%	θ/(°)	d/m	γ_i/%	θ/(°)	d/m	γ_i/%	θ/(°)		
Initial route	15 263	7		425	7	87	47 524	7	163	49 530	7	92	0.423 9	0.698 3
Optimal route	13 500	6		9 893	5	92	36 906	7	171	48 424	0	180	0.976 4	0.984 5

to bypass b_4. Table 1 shows the comparison results before and after route optimization.

(2) Network optimization of departure routes

According to principles of optimization sequence and the actual air traffic flow of Xiaan Airport, optimization order of the departure routes is determined as $R_{d1} < R_{d2} < R_{d4} < R_{d3}$. Here, it is unnecessary to consider the vertical separation and lateral separation requirements between departure routes. The results are shown in Fig. 5.



(a) Results for departure route network

(b) Results for arrival route network

Fig. 5 Optimization results for arrival and departure route network

(3) Network optimization of arrival routes

The arrival route optimization is achieved based on departure route optimization, and the optimization order is $R_{a1} < R_{a2} < R_{a3}$. Take the optimized departure route as a vacant restricted area according to Section 4.2, and then designate a rectangular protected area to optimize arrival route routes with the optimization order, as shown in Fig. 5(b).

Route R_{a1} and departure route R_{d2} intersect at point A. The distance between A and the ground end of route R_{d2} is 94 720 m, while the distance between A and the ground end of route R_{a1} is 112 900 m. The vertical separation at that point can be calculated as $d_{z\_A} = 1\ 093$ m using Eq. (18), as shown in Figure 6. Routes R_{a1} and R_{d1} intersect at point B, and the vertical separation $d_{z\_B} = 316$ m. Without considering the constraints of the vertical and lateral separation, the optimization result of route R_{a2} is the dotted line in Fig. 5(b). Taking $d_a = 1\ 000$ m, the lateral separation of R_{a2} can be obtained as $d(R_{a1}, R_{di}) = 3\ 260$ m according to Section 4.3, which apparently does not satisfy the lateral separation requirements. If we use the Eq. (16) to reduce pheromones of waypoint in the horizontal direction and enlighten the route to bypass obstacles, obvious shift can be achieved. Thus, the arrival route would intersect with departure routes R_{d3} and R_{d1} at points C and D, and vertical separation requirements can be satisfied , as shown in Fig . 6 . Table 2 shows

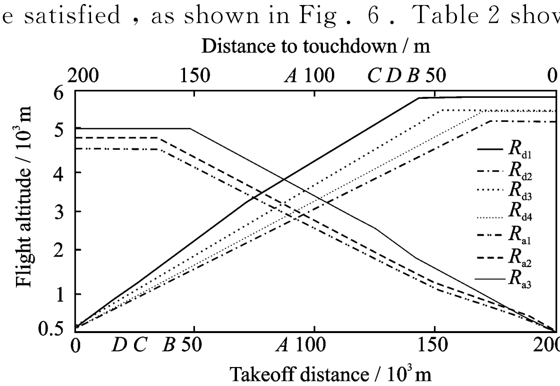


Fig. 6 Vertical profile of departure and arrival routes

Table 2 Optimization results of arrival and departure routes

Parameter	Seg1		Seg2			Seg3			Seg4			Seg5			Seg6			Seg7			$\mu_{\tilde{H}}(R)$	$\mu_{\tilde{V}}(R)$
	d/ km	γ_i/ %	d/ km	γ_i/ %	θ/ (°)	d/ km	γ_i/ %	θ/ (°)	d/ km	γ_i/ %	θ/ (°)	d/ km	γ_i/ %	θ/ (°)	d/ km	γ_i/ %	θ/ (°)	d/ km	γ_i/ %	θ/ (°)		
R_{d1}	13.5	6	9.9	7	92	36.9	7	171	48.4	0	180										0.976 4	0.984 5
R_{d2}	12.0	6	82.1	5	156	32.2	7	179	32.7	0	179										0.985 1	0.865 9
R_{d3}	10.5	7	16.3	7	94	90.6	0	137													0.968 9	1
R_{d4}	10.5	7	16.3	7	94	105.2	6	137													0.967 7	0.995 7
R_{a1}	10.0	3	45.1	3	178	562.1	3	180	278	3	180	37.5	0	180							0.998 6	1
R_{a2}	23.4	3	6.9	2	180	16.8	2	179	16.5	3	108	9.1	3	157	50.8	3	114	77.6	0	171	0.943 3	0.989 5
R_{a3}	10.3	3	40.5	3	179	52.3	3	180													0.997 9	1

the results of network optimization of arrival/departure route.

The algorithm could create a satisfactory route only with a starting point and an ending point. The parallel runways usually have different IAF, and the arrival route will has different ending points correspondingly, so it can be considered as two independent arrival routes. After passing their own initial approach fix, aircraft will be assigned a landing runway dynamically by air traffic controller according to present operation situation, and this is beyond the airspace planning area. It should be noted that the route planning method is independent from runway-in-use.

(4) Algorithm iteration process

As reported in Ref. [9], when four routes were optimized with A* algorithm, the optimization time was 43 s; while for 8 routes , the optimization time was 4 h. Obviously, search time is greatly affected by the number of routes, mainly because the large searching space can not constrain the new route search by optimized routes. Therefore, we divide the terminal airspace with MAKLINK line, and the route searching scope can be directly determined by the initial route. Thus, most routes can reach or approach the optimal solution in 300 iteration times. As shown in Fig. 7, the algorithm running time is 63 s, and the efficiency is greatly improved without being affected by the number of routes to be optimized.

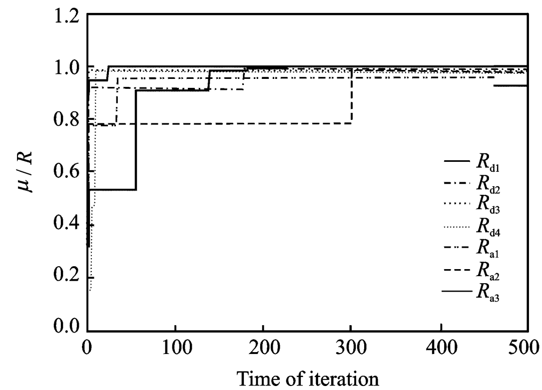


Fig. 7 Convergence process of route optimization solution

6 Conclusions

Arrival and departure routes planning is an important foundation for safety and efficiency of air traffic operations. A two-stage method is adopted to achieve the route network optimization and design: the path finding of individual route is realized first, and then individual route is optimized one by one. Finally, a route network is constructed according to the priority under the constraints of the previous optimization results. For the choice of individual route waypoints, a probabilistic searching method, working along the horizontal direction first and then the vertical direction, is presented. Therefore, the path search algorithm in 3D space can be realized with an improved ant-colony algorithm.

The terminal airspace model is constructed with visual diagram, which effectively reduces the search space. Therefore, the search efficiency of flight routes has heen greatly improved, and the problem that the search time increases significantly with the increase of route number in A* algorithm has been solved.

Our future work will focus on the convergence of multiple arrival routes. Arrival routes are generated in turns according to the principles of optimization sequence, but it is still necessary to be studied intensively that how the successive route joins into the previous ones.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (No. 61039001), the State Technology Supporting Plan (No. 2011BAH24B08), and the Fundamental Research Funds for the Central Universities (No. ZXH2011A002).

References:

[1] Tian Qingfei. Study on urban transit network generation and optimization based on complex network theory[D]. Changchun: Jilin University, 2013: 3-18. (in Chinese)

[2] Wang Wei, Yang Xinmiao, Chen Xuewu. Urban public transportation system planning method and management technology[M]. Beijing: Science Press, 2002: 77-95. (in Chinese)

[3] Chen Xin. The strategy of optimization and planning for urban traffic network[D]. Wuhan: Huazhong University of Science and Technology, 2005. (in Chinese)

[4] Zhang Yongfang, Zhang An, Zhang Zhiyu. Planning algorithm of tactics flight path[J]. Journal of Traffic and Transportation Engineering, 2006, 6(4): 84-87. (in Chinese)

[5] Beard R W, McLain T W, Goodrich M A, et al. Coordinated target assignment and intercept for unmanned air vehicles[J]. IEEE Transactions on Robotics and Automation, 2002, 18(6): 911-922.

[6] Zheng C, Li L, Xu F, et al. Evolutionary airline planner for unmanned air vehicles[J]. IEEE Transactions on Robotics, 2005, 21(4): 609-620.

[7] Chen S B, Jiang J P. Research on path planning and trajectory tracking of autonomous mobile robot[D]. Hangzhou: Zhejiang University, 2008. (in Chinese)

[8] Gorbenko A, Popov V. Self-learning algorithm for visual recognition and object categorization for autonomous mobile robots[M]. Computer, Informatics, Cybernetics and Applications. Netherland: Springer, 2012: 1289-1295.

[9] Pfeil D M. Optimization of airport terminal-area air traffic operations under uncertain weather conditions [D]. California, USA: University of California at Berkeley, 2011.

[10] Eurocontrol. Airspace concept handbook for the implementation of performance based navigation[EB/OL]. (2013-12-10)[2015-12-22]. http://www.eurocontrol.int/sites/default/files/publication/files/handbo-ok-pbn-implement-2013-ed-3a.pdf.

[11] International Civil Aviation Organization. A-2-2: A-2-5—1996, DOC 8168-OPS/611 Air Navigation Service-Aircraft Operations[S]. China: ICAO Montreal, 1996. (in Chinese)

[12] Wang Chao. Research on evaluation theory and simulation application of flight procedure Operation [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2012. (in Chinese)

[13] Wang Chao, Wang Fei. Multi-objective intelligent optimization of noise abatement departure trajectory [J]. Journal of Southwest Jiao tong University, 2013, 48(1): 147-153. (in Chinese)

[14] Habib M K. Efficient method to generate collision free paths for autonomous mobile robot based on new free space structuring approach[J]. IEEE/RSJ International Workshop on Intelligent Robots and System, 1991, 91(6): 563-567.

[15] Baase S, Gelder A V. Computing algorithms[M]. Beijing: Higher Education Press, 2001: 235-267.

[16] Xu Jingming, Cao Xianbing, Wang Xufa. Polymorphic ant colony algorithm[J]. Journal of University of Science and Technology of China, 2005, 35 (1): 59-65. (in Chinese)

(Executive Editor: Zhang Bei)