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Optimization of Conflict-Free Airline Network Designing

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Abstract. This paper focuses on the issue of planning and optimization of airline network under PRD (Prohibited Area, Restricted Area and Danger Area) avoiding, in a way of hierarchical and quantitative design. According to the principle of Maklink Graph method, the issue of optimization of airline network was transformed to the issue of optimization of non-interference path point distribution. A method of addition of virtual path point was proposed to solve the problem of traffic jam in the airlines, and a Differential Evolution Algorithm was adopted to solve the model of the virtual path point distribution. In the end, a few representative performance indexes were chosen to evaluate the optimized airline network, and the evaluation result has proved that the method proposed in this paper to plan and optimize the airline network was reasonable and effective.

Introduction

In ideal conditions, in order to improve the execution efficiency and lower the entire cost of airline network, the airlines which connect airport pairs in straight line should be established [1]. However, because of the restrictions on safety of airspace operation and the conflicts between airline network and PRDs, the airline planning between airport pairs should transit through some path points without interference to accomplish the preliminary designing of conflict-free airline network [2], as shown in the figure 1.

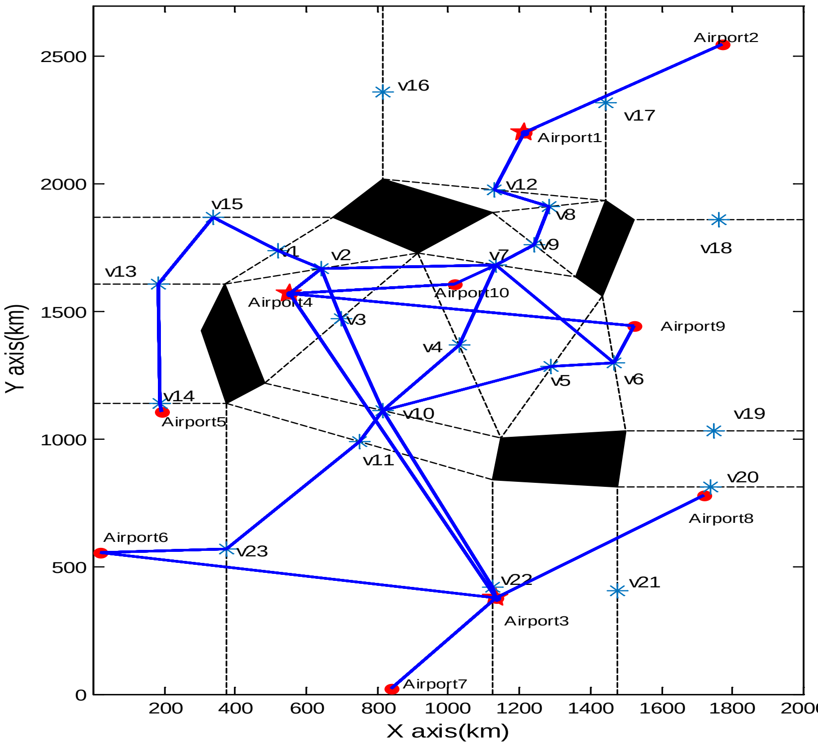

Figure 1 Preliminary designing of conflict-free airline network

The quantity and spatial distribution of these path points without interference (middle points of free connected lines in Maklink graph) decides the topological property and connection characteristics of airline network, and directly affects the evaluation of airline network operation. Therefore, it is necessary to adjust the layout of path points keep the balance between safety of airspace and minimizing entire cost of airline network in a tolerable level. Based on the theory of Maklink graph, the position of path points can be slid within limits to optimize the preliminary designing of conflict-free airline network.

Non-interference path points layout model

The key issue of optimization of conflict-free airline network lies in the optimal position of non-interference path points. Therefore, all of these path points should be optimize in an integral whole to meet the needs of air transportation and airspace restriction.

Problem description. Based on the description above, a few hypotheses are proposed before establishing the non-interference path points layout model:

I. The airline network is designed in 2D surface without regard to the information of altitude.;
II. Planes fly straight from one point to another unconditionally, and airlines between airport pairs is the shortest path in the network;
III. PRDs are impenetrable for any airlines;
IV. The entire cost of airline network depends on the length of every airline.

Modeling building. The preliminary designing of conflict-free airline network can be expressed as $N(V,D,T,B)$:

I. $V(N)$ indicates to a collection of nodes in the network, including non-interference path points and airport nodes. The number of the two kinds of nodes are respectively denoted as n and m:

$$V=\{v_1,v_2,\cdots,v_n,v_{n+1},\cdots,v_{n+m}\} \tag{1}$$

II. $D(N)$ indicates to the distance matrix of any pair of nodes in the network. The position of node v_i is denoted as (x_i,y_i), then the element d_{ij} in the distance matrix can be defined as follows:

$$d_{ij}=\begin{cases}\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}, & [v_i,v_j]\neq 0;\\ 0, & else.\end{cases} \tag{2}$$

III. $T(N)$ indicates to a collection of PRDs. For the safety of airline network, the intersection of airline and PRDs must be empty set.:

$$path(v_i,v_j)\bigcap T(N)=\varnothing \tag{3}$$

In equation (3), $path(v_i,v_j)$ indicates to the airline from node v_i to v_j.

IV. $B(N)$ indicates to considerable freedom for the position of non-interference path points:

$$x_{i\min}\le v_{ix}\le x_{i\max},\ y_{i\min}\le v_{iy}\le y_{i\max} \tag{4}$$

Based on the property of Maklink graph [3], the airline would not have conflict with PRDs if the path points keep shifting on the free connected lines. Therefore, this property can be used to accomplish the PRDs avoidance for airline network designing. Supposing that the corresponding free connected line of path point v_i is $L_i(i=1,2,\ldots,n)$, $v_i^{(0)}$ and $v_i^{(1)}$ are two vertexes of L_i. Then the position of path point v_i on L_i can be expressed as follows:

$$v_i=v_i^{(0)}+(v_i^{(1)}-v_i^{(0)})\times h_i,\qquad h_i\in(0,1) \tag{5}$$

In equation (5), h_i is a scaling parameter which determine the position of v_i.Figure 2 shows the process of a path point shifting on the free connected line.

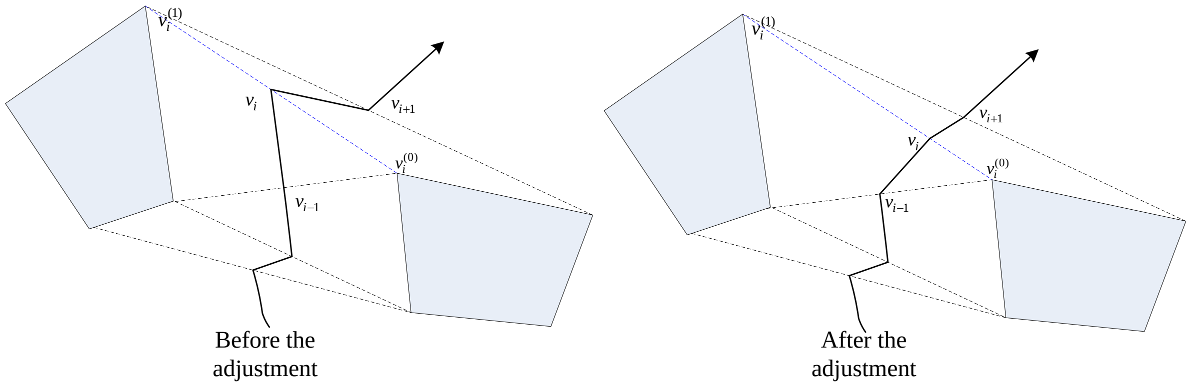

Figure 2 Adjustment of path point based on Maklink graph

In conclusion, the the layout optimazition model of non-interference path points can be expressed as follows:

$$Min \qquad \sum_{i=1}^{n+m}\sum_{j=1}^{n+m} d_{ij} / 2 \tag{6}$$

$$S.T. \qquad v_i = v_i^{(0)} + (v_i^{(1)} - v_i^{(0)}) \times h_i, \qquad h_i \in (0,1) \tag{7}$$

$$\min(v_{ix}^{(0)}, v_{ix}^{(1)}) < v_{ix} < \max(v_{ix}^{(0)}, v_{ix}^{(1)}) \tag{8}$$

$$\min(v_{iy}^{(0)}, v_{iy}^{(1)}) < v_{iy} < \max(v_{iy}^{(0)}, v_{iy}^{(1)}) \tag{9}$$

From the model above, we can figure that once a set of scaling parameters is given, there would not be any conflict between airline netwokr and PRDs. Therefor, the laout opimaztion problem can be seen as a funciton minimization problem of non-differentiale continuous space, and this paper adopts an applicable intelligent optimization algorithm to solve this model.

Differential evaluation agorithm design

Stron R and Price K proposed the differential evaluation (DE) algorithm in 1995 [4]. Similar with Particle Swarm Optimization algorithm, DE is algorithm based on swarm intelligence which guidance the search process through cooperation and competition among individuals. Compared with Genetic Algorithm (GA), DE reduces the complexity of the genetic operation based on one-to-one competition survival strategy.

Consideration for application issues. The non-interference path points would be used to be translation nodes to eliminate the conflict between airline network and PRDs. Therefore, there would be a situation that a few airlines use the same path point to translate which substantially increases the fight flow of airlines and reduces safety of network. This paper proposed a method of adding virtual path points to solve the problem of traffic jam in the airlines. As showed in figure 3, these repetitive non-interference path points can be broken down into two or more to handle.

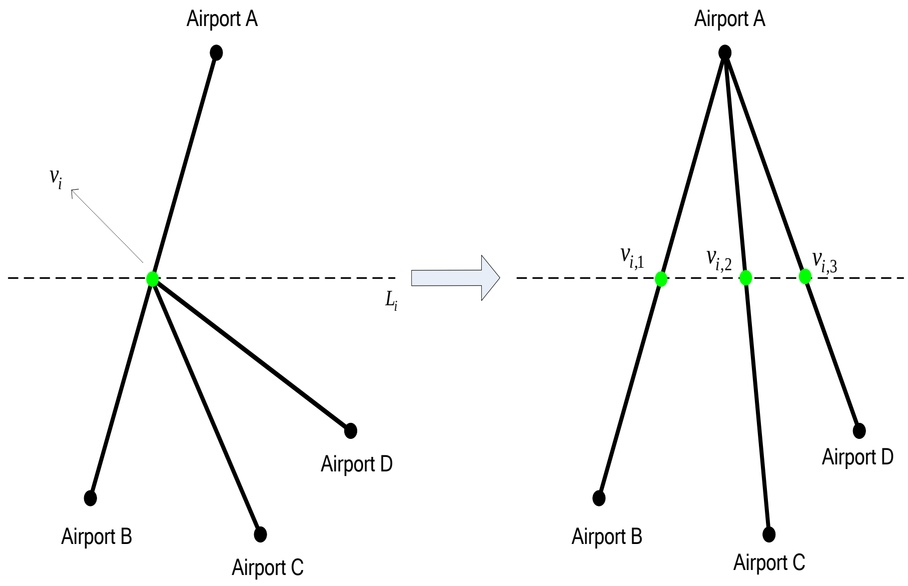

Figure 3 Decomposition of non-intereference path point

Algorithm process. Detailed steps of DE algorithm:

Step1 Encoding:

Supposing that the preliminary designing of conflict-free airline network $N(V,D,T,B)$ has $n+m$ vertexes, which means n path points (including q virtual path points) and m airport points. Treat the set of vertexes as a real vector $[v_{1x}, v_{1y},\ v_{2x}, v_{2y},\ \ldots\ , v_{nx}, v_{ny},\ \ldots\ , v_{(n+m)x}, v_{(n+m)y}]$. Thereinto, $[v_{ix}, v_{iy}]$ is the coordinate of node i:

$$\begin{cases} v_{ix} = v_{ix}^{(0)} + (v_{ix}^{(1)} - v_{ix}^{(0)}) \times h_i \\ v_{iy} = v_{iy}^{(0)} + (v_{iy}^{(1)} - v_{iy}^{(0)}) \times h_i \\ h_i \in (0,1) \end{cases} \tag{10}$$

Step2 Evaluation criterion:

This paper adopts objective function (6) as the evaluation criterion of individuals.

Step3 Population initialization:

According to the quantity of path points, a sequence is generated randomly as an individual, and repeats the process of individual generation until touching the population size:

$$\boldsymbol{x}_i = ind(i,:) = rand(1,n)\ ,\ i = 1,2,\ldots,NP \tag{11}$$

Step4 Mutation operation:

Select randomly 3 individuals $\boldsymbol{x}_{r_1}$, $\boldsymbol{x}_{r_2}$ and $\boldsymbol{x}_{r_3}$ in current population and make a differential vector:

$$\boldsymbol{D}_{r_{2,3}}(g) = \boldsymbol{x}_{r_2}(g) - \boldsymbol{x}_{r_3}(g) \tag{12}$$

Add the differential vector above to individual $\boldsymbol{x}_{r_1}$ to get the target individual:

$$\boldsymbol{t}_i(g) = \boldsymbol{x}_{r_1}(g) + F \bullet \boldsymbol{D}_{r_{2,3}}(g) \tag{13}$$

Step5 Individual repair:

After mutation, target individual $\boldsymbol{t}_i(g)$ should be checked to ensure that $\boldsymbol{t}_i(g)$ meets the constraint range:

$$\begin{cases} new\_h_{i,j} = 1 + rand \times (h_{i,j} - h_{i\max}), & h_{i,j} \geq 1 \\ new\_h_{i,j} = 0 + rand \times (h_{i,j} - h_{i\min}), & h_{i,j} \leq 0 \end{cases} \tag{14}$$

Step6 Crossover operation:

$$v_{i,j}(g)=\begin{cases} t_{i,j}(g), & rand < cr或j = rnd \\ x_{i,j}(g), & else \end{cases} \quad (15)$$

Step7 Selection operation:

$$\boldsymbol{x}_i(g+1)=\begin{cases} \boldsymbol{v}_i(g), & f[\boldsymbol{v}_i(g)] < f[\boldsymbol{x}_i(g)] \\ \boldsymbol{x}_i(g), & else \end{cases} \quad (16)$$

Step8 Current optimal solution updating.

Step9 Iteration.

Optimization result and evaluation. According to the algorithm process above, this paper solutes the non-interference path points layout model in platform MATLAB 2014a and accomplish the optimization of preliminary designing of conflict-free airline network, figure 4 shows the optimization results:

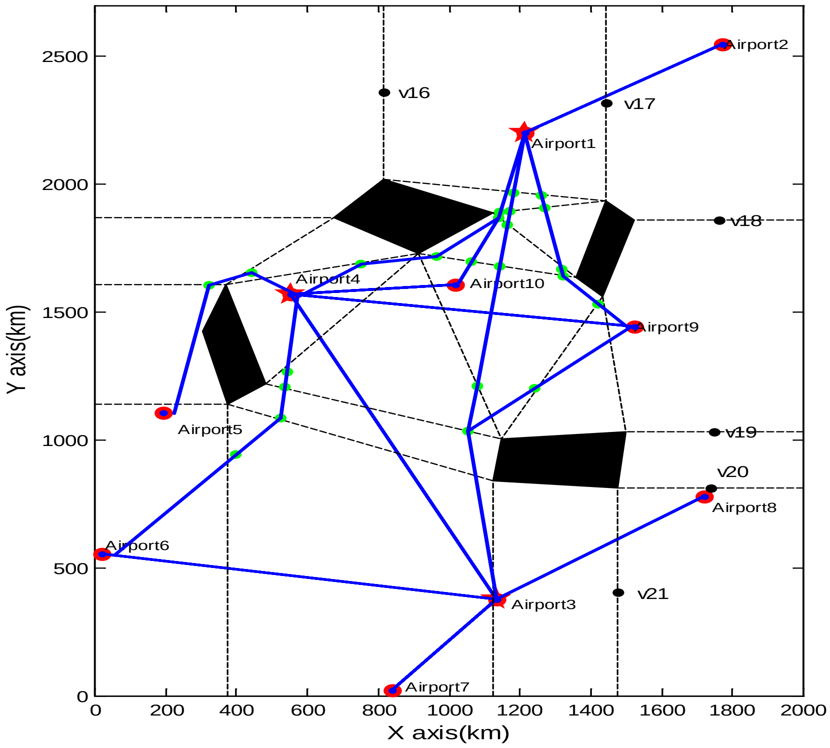

Figure 3 Optimization results of airline network

This paper adopts some representative evaluation indexes [5] such as network length, airway utilization, operating cost and nonlinear coefficient to compare the airline network of before and after optimization.

Table 1Comparison of airline network before and after optimization

Evaluation Indexes	Before Optimization	After Optimization	Dimension
Path Points	20	8	-
Number of Legs	28	22	-
Nonlinear Coefficient	1.39	1.16	-
Network Length	17827.15	14814.36	km
Operating Cost	562.78×10^{4}	491.81×10^{4}	km·sortie/week
Airway Utilization	4.08×10^{-2}	4.91×10^{-2}	sortie/km·week
Reachability	594.24	823.02	km

Summary

From the comparison in Table 1 we can figure out that all of the evluation indexes of optimized airline network are superior to the ones before optimization. Thereinto, the number of path points has been reduced by 60%, while 16.% for nonlinear coefficient, and 12.6% for operating cost; the airway utilization has been improved by 20.3% while 38.4% for reachability. Quantitative and comparative analysis before and after optimization has fully illustrated the necessity and effectiveness of the optimizaiton method proposed in this paper.

References

[1] Zheng-Wei Xin. Research on Technique of Air Route Network. Nanjing: Nanjing University of Aeronautics and Astronautics, 2013.

[2] Jonh S, Kazuo S. Genetic Algorithms for Adaptive Motion Planning of an Autonomous Mobile Robot[C]. Computational Intelligence in Robotics and Automation. 1997:138-143.

[3] Maki K, Hajime Asama. Efficient Method to Generate Collision Free Paths For Autonomous Mobile Robot Based on New Free Structuring Approach. IEEE/RSL International Workshop On Intelligent Robots and System IROS'91,Nov.35, 1991, Osaka, Japan.IEEECat.No.91TH0375-6.

[4] Storn R, Price K. Differential evolution—a simple and efficient heuristic for global optimization over continuous spaces. J of Gloval Optimization, 1997,11(4): 341-359.

[5] FAA ATA-301.Advisory Circular: High Altitude Airspace Redesign Phase 1[R].USA: AC.2003:90-99.