Track Planning for Intelligent Aircraft Under Multiple Constraints

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Abstract

Track planning in complex environment is an important subject of intelligent aircraft control. Due to the limitation of system structure, the positioning system of such aircraft cannot accurately locate itself. Once the positioning error accumulates to a certain degree, the mission may fail. Therefore, it is an important task to correct positioning errors in the path. This article studies track planning of intelligent aircraft under the limitation of positioning accuracy. On the basis of the assumptions, not only three problems are proposed, but also the statistical analysis of the problems is carried out.

Keywords

Intelligent aircraft, Track planning, Nsga2 algorithm.

1. Introduction of the problem

Aircraft has actual position during the flight, and its positioning error includes vertical error and horizontal error. For each 1m flight of the aircraft, the vertical error and the horizontal error will each be increased by a specific unit, hereinafter referred to as the unit. The vertical and horizontal error should be less than θ units, and to simplify the problem, assuming that when vertical and horizontal errors are less than θ units, aircraft could fly according to the plan.

During the flight, the aircraft needs to correct the positioning error. There are some safe positions, also called correction points, in the flying area that can be used for error correction. When aircraft reaches the correction point, error correction can be carried out. The correction points are determined in advanced (figure 1 is a schematic diagram of a track, yellow points are the horizontal error correction points, blue points are the vertical error correction points, the starting point is A, the destination is B, and the black curve represents a track). If vertical and horizontal errors can be corrected in time, the aircraft can fly according to the scheduled route, and finally reach the destination. At point A, the vertical and horizontal errors of the aircraft are both 0. After the aircraft conducts vertical error correction at the vertical error correction point, its vertical error will become 0, and the horizontal error will remain unchanged.

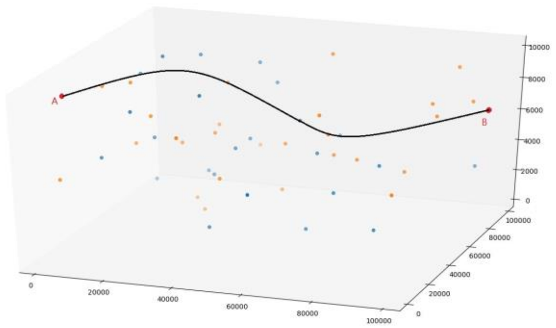

Figure 1: schematic diagram of flight path

Similarly, after the aircraft conducts horizontal error correction at the horizontal error correction point, its horizontal error will become 0, and the vertical error will remain unchanged. Only when the vertical error of the aircraft is no more than $\alpha 1$ unit, and the horizontal error is no more than $\alpha 2$ units, can the vertical error be corrected. Only when the vertical error of the aircraft is no more than $\beta 1$ unit and the horizontal error is no more than $\beta 2$ units can the horizontal error be corrected.

In this article, we raised three problems as follows:

Problem 1: According to the data in attachment 1 and 2, the aircraft's flight path has to meet the following optimization objectives: (A) The length of flight path is as short as possible; (B) The aircraft passes through as few correction points as possible. Discuss the effectiveness and complexity of the algorithm.

Problem 2: The aircraft is limited by the structure and control system during the turning, so it cannot complete the turning immediately since the forward direction of the aircraft cannot be changed suddenly. It is assumed that the minimum turning radius of the aircraft is 200m. Take this condition into consideration and discuss the effectiveness of the algorithm.

Problem 3: The flight environment may change over time, although the calibration points have been confirmed, the aircraft is unable to achieve ideal correction as a certain error correction to 0. For example, weather is an uncontrollable factor which may cause the aircraft to vary from the ideal error correction. Assumes that the probability of error correction to 0 is 80%, otherwise, the correction of residual error is min (error, 5) units. In this case, discuss the effectiveness of the algorithm.

2. Problem Analysis

2.1 Problem 1:

The objective of reducing the number of correction points may not positively correlated with the objective of reducing the total distance, especially in the optimization problem with such complex constraints. Therefore, it is intended to adopt the multi-objective optimization algorithm. Here, nsga2 algorithm is considered. Nsga2 algorithm is improved on the basis of nsga. Nsga2 is one of the most popular multi-objective genetic algorithms. It reduces the complexity of non-inferior sorting genetic algorithm. Thus nsga2 has the advantages of fast running speed and convergence, and has become the benchmark of multi-objective optimization algorithms.

Nsga2 can retain the most outstanding individuals by reducing the complexity of calculation. In addition, nsga2 could ensure that excellent individuals will not be abandoned in the process of evolution so as to improve the accuracy of the optimization results. Moreover, by using crowding degree comparison operator, we could not only overcome the need to manually specify parameters, but also can we evenly expand quasi-pareto domain to the whole Pareto domain, to ensure the diversity of the population. The purpose of nsga2 is to select N individuals from the current M individuals.

The key to multi-objective optimization problem of fast non-dominant sorting algorithm is to obtain the optimal Pareto solution set. Nsga2 non-dominant ordering is used to stratify population M according to the level of non-inferior solution of individuals to obtain Fi, which makes the Pareto optimal solution. It is a cycle of adaptive value grading process. First of all, we need to find the dominant group in solution set, marked as F1. Individuals in the F1 are given rank = 1. Second, we need to remove F1 from the whole group M, then continue to find the disposal solution set, which is F2. Individuals in the F2 are given rank = 2. Continue the process until all individuals are assigned.

2.2 Problem 2:

The main difference of this problem is that problem 2 has one more maneuver limit, so it is necessary to estimate the radius of curvature of the currently planned path. If the radius of curvature of the current node is too small, the constraint will not be satisfied. It is necessary to consider how to maneuver after the radius of curvature meets the requirements. The elite strategy selection algorithm keeps the excellent individuals in the parent generation to prevent the loss of Pareto optimal solution. In order to prevent Pareto optimal solution from losing, it is necessary to keep the superior individuals in the parent generation.

For deciding individual crowding distance in the same level of Fi, we use selective sorting, which is sorted according to crowding distance. The crowding distance of individuals is the distance between individuals i +1 and i -1 adjacent to i. The calculation steps are as follows:

(1)Initialize the individual distance of the same layer, let L[i]d=0, L[i]d represents the crowding distance of any individual i.

(2) Sort individuals in ascending order according to the objective function value.

(3) Give selection advantage for individuals on the edge of the ranking.

(4) Sort the middle of individuals and find the crowding distance.

For different objective functions, repeat the steps from (1) to (4) to get the crowding distance L[i]d of individual i, and give priority to the individuals with larger crowding distance, so that the calculated results can be evenly distributed in the target space to maintain the diversity of the group.

2.3 Problem 3:

Probability is taken into consideration in problem 3, we use the Monte Carlo simulation. To put it bluntly, the simulation is repeated over and over again, and then the number of successes and failures is counted to approximate the real probability. The first two questions do not need to take probability into consideration, one path only runs once, and the third question has probability, so we run k times to calculate the probability of success once the path contains the correction point of probability 0.8.

2.4 Model assumptions

It is assumed that the aircraft can know whether it can be corrected successfully when it reaches the correction point. However, no matter the correction is successful or not, the planned path cannot be changed.

3. Modelling

Table 1 Description of modeling symbols

Symbol	Meaning
S_i	Distance between node i-1 and node i
ε_{H_i}	Horizontal error at node i
ε_{V_i}	Vertical error at node i
y	Function of the turning circle
FP	Probability of failure

3.1 Problem 1

Objective function:

$$\min \sum_{i=1}^{N} S_i \quad \text{, where } S_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2}$$

$$\min \quad \sum_{i=1}^{N} (I(\varepsilon_{H_i} \le \alpha_2, \varepsilon_{V_i} \le \alpha_1) + I(\varepsilon_{V_i} \le \beta_1, \varepsilon_{H_i} \le \beta_2))$$

$$\begin{cases} \varepsilon_{V_0} = 0, \varepsilon_{H_0} = 0 \\ \varepsilon_{V_{i+1}} = \varepsilon_{V_i} + \delta S_i \\ \varepsilon_{H_{i+1}} = \varepsilon_{H_i} + \delta S_i \end{cases}$$

Constraints:

$$\frac{\partial \varepsilon_{V_i}}{\partial S_i} = \delta$$
$$\frac{\partial \varepsilon_{H_i}}{\partial S_i} = \delta$$
$$\sum_{i=0}^{N} \varepsilon_{V_i} < \theta$$
$$\sum_{i=0}^{N} \varepsilon_{H_i} < \theta$$

If $\varepsilon_{H_i} \le \alpha_2, \varepsilon_{V_i} \le \alpha_1$ then $\varepsilon_{V_{i+1}} = 0$

If $\varepsilon_{V_i} \le \beta_1, \varepsilon_{H_i} \le \beta_2$; then $\varepsilon_{H_{i+1}} = 0$

Since the problem imposes many constraints on the solution, we can add a strategy to the initial solution generation process to reduce the invalid solution. If the distance between two correction nodes exceeds the maximum unit error, the solution is invalid. When the next node is generated, the distance between nodes must be less than a fixed value, namely the maximum error. The error can only be corrected after the node reaches the next correction point, so the current error margin constrains the distance of the future solution. In addition, the X-axis correction node and Y-axis correction node need to be separated from each other. Our goal is to fly from A to B, so we're going to make the probability of the node closer to B when we pick the next node. Each node can only be used once. After the node reaches the vicinity of B, it tries to connect to B directly. If it succeeds, it will be pushed out.

The new solution strategy is still essentially path planning through the crossover behavior, so the better way to cross the two path solutions is to take a point of each solution and divide the two paths into four, and then combine the two paths to get two new solutions. The choice of points depends on the distance. Because of the existence of constraints, two optimization strategies are set, one is to exchange two nodes on the path, and the other is to eliminate a node.

3.2 Results of problem 1

Data set 1

Table 2 Results of data set 1 of problem 1

Correction point number	Vertical error before correction	Horizontal error before correction	Correction type
1	0	0	A
504	13.387920	0	01
70	0	8.807346	02
238	12.499484	0	01
234	0	10.823958	02
599	14.004883	0	12
316	0	7.314304	02
486	14.510063	0	12
249	0	4.220560	02
613	19.513453	23.734012	B

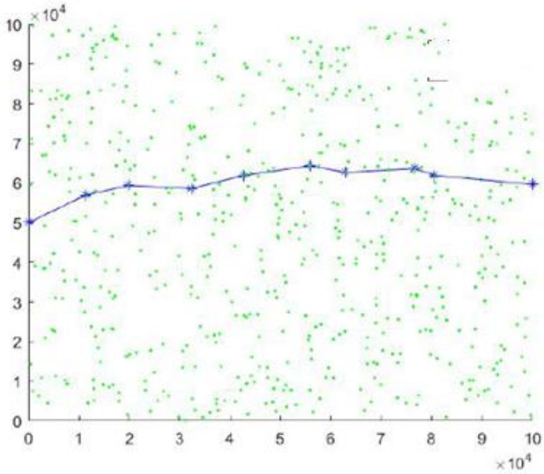

Figure 2 Flight route of data set 1 of problem 1

Data set 2

Table 3 Results of data set 2 of problem 1

Correction point number	Vertical error before correction	Horizontal error before correction	Correction type
1	0	0	A
141	5.655758	0	01
151	0	6.756807	02
239	10.945923	0	01
235	0	2.347546	11
310	13.311634	0	12
306	0	5.968718	02
124	9.204398	0	12
232	0	9.436722	11
161	8.717174	0	01
93	0	5.776166	11
94	9.484715	0	01
39	0	6.296536	02
111	3.92654	0	12
100	0	9.199885	02
327	8.649597	17.849482	B

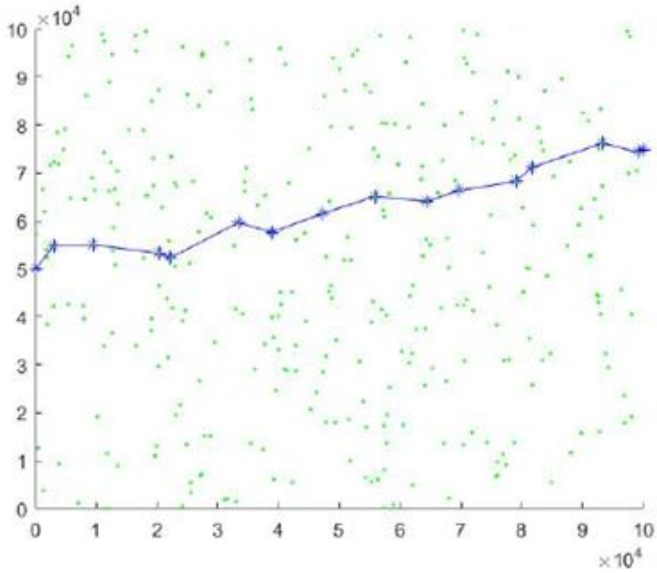

Figure 3 Flight route of data set 2 of problem 1

We use Matlab to create the results above. The code generates the initial solution through the appropriate strategy and avoids a large number of invalid solutions, so that the optimization can start from a more appropriate location. Although local optimization may occur, the applicability is still strong. In terms of complexity, the main complexity of the algorithm is the generation phase of the initial solution.

3.3 Problem two

Objective function:

$\min \sum_{i=1}^{N} S_i$, where $S_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2}$

$$\min \quad \sum_{i=1}^{N} (I(\varepsilon_{H_i} \le \alpha_2, \varepsilon_{V_i} \le \alpha_1) + I(\varepsilon_{V_i} \le \beta_1, \varepsilon_{H_i} \le \beta_2))$$

$$\begin{cases} \varepsilon_{V_0} = 0, \varepsilon_{H_0} = 0 \\ \varepsilon_{V_{i+1}} = \varepsilon_{V_i} + \delta S_i \\ \varepsilon_{H_{i+1}} = \varepsilon_{H_i} + \delta S_i \end{cases}$$

Constraints:

$$\frac{\partial \varepsilon_{V_i}}{\partial S_i} = \delta$$

$$\frac{\partial \varepsilon_{H_i}}{\partial S_i} = \delta$$

$$\sum_{i=0}^{N} \varepsilon_{V_i} < \theta$$

$$\sum_{i=0}^{N} \varepsilon_{H_i} < \theta$$

If $\varepsilon_{H_i} \le \alpha_2, \varepsilon_{V_i} \le \alpha_1$ then $\varepsilon_{V_{i+1}} = 0$

If $\varepsilon_{V_i} \le \beta_1, \varepsilon_{H_i} \le \beta_2$ then $\varepsilon_{H_{i+1}} = 0$

$$\left| \frac{\left(1+y'^2\right)^{\frac{3}{2}}}{y''} \right| \geq 200$$

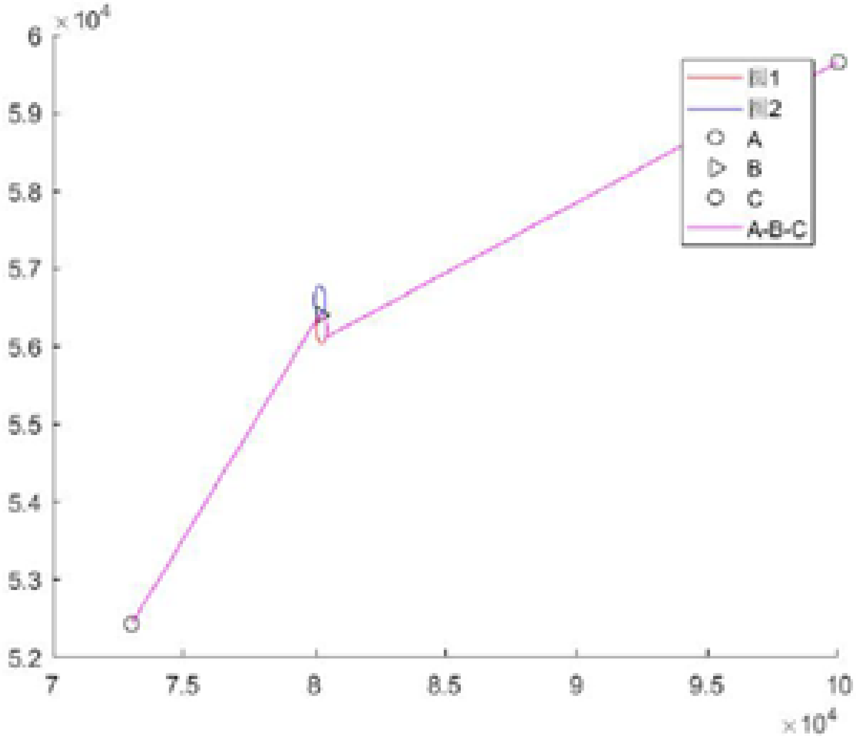

Figure 4 Schematic diagram for problem 2

Path from A pass through B to C, find a circle with radius of 200m over B, and then find two points D and E on the circle, so that AD and CE are tangent to the circle respectively. Therefore, the additional constraint condition of problem two is transformed into a geometric problem. In addition, two tangent lines can be calculated by three known points and the center of two circles can be found. Then, the equation of the circle can be written out and the radius of curvature can be calculated.

New solution generation process:

1. Calculate the distance between all nodes of two paths.
2. Find a set of nodes whose distance is less than the set value.
3. Use the reciprocal of the distance as the roulette wheel weight.
4. Select a set of nodes for roulette.
5. Take this group of nodes as the dividing line and divide the two paths into four paths.
6. Four paths are combined in pairs to create two new paths.
7. Determine whether the new solution has at least one feasible solution, repeat 1-6 until a feasible solution is found.
8. Output the feasible solution.

Variation mode 1

1. Select any point on the path to exchange with the point nearby.
2. Determine whether the feasible solution is found, repeat 1 until the feasible solution is found.

Variation mode 2

1. Select any point in the path to remove.
2. Determine whether the feasible solution is found, repeat 1 until the feasible solution is found.

3.4 The results of problem 2

Data set 1

Table 4 Results of data set 1 of problem 2

Correction point number	Vertical error before correction	Horizontal error before correction	Correction type
1	0	0	A
286	13.477387	0	01
304	0	7.886237	11
367	14.694174	0	12
16	0	8.478944	02
143	14.957466	0	01
251	0	8.787285	11
341	12.785753	0	01
584	0	8.932078	02
613	20.228904	29.160982	B

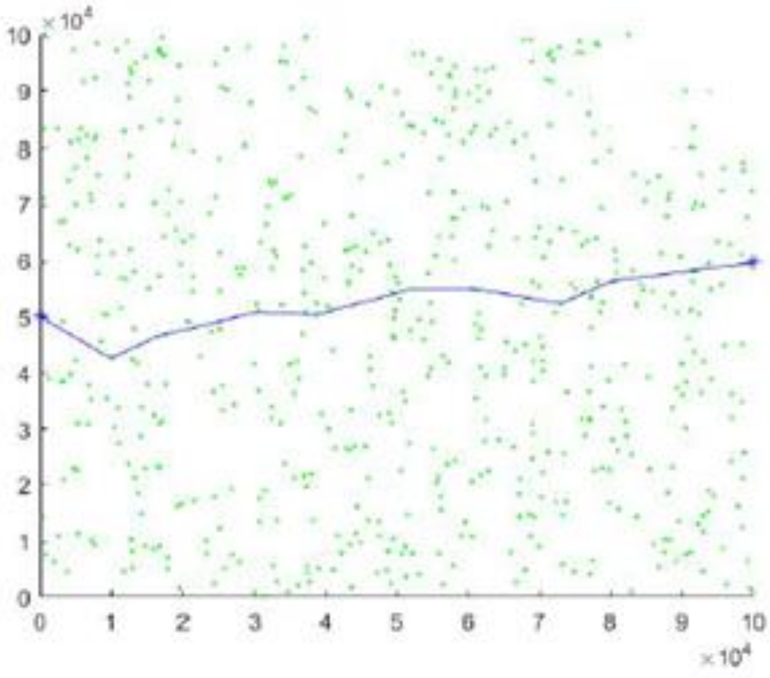

Figure 5 Flight route of data set 1 of problem 2

Data set 2

Table 5 Results of data set 2 of problem 2

Correction point number	Vertical error before correction	Horizontal error before correction	Correction type
1	0	0	A
141	5.983193	0	01
151	0	6.971175	02
239	11.031769	0	01
235	0	2.383481	11
310	13.314435	0	12
231	0	5.158057	02
124	11.343481	0	12
171	0	3.124458	02
42	12.583313	0	12
222	0	3.769112	11
20	9.72367	0	12
51	0	7.977776	02
97	11.425208	0	01
62	0	6.459119	02
327	12.321541	18.780660	B

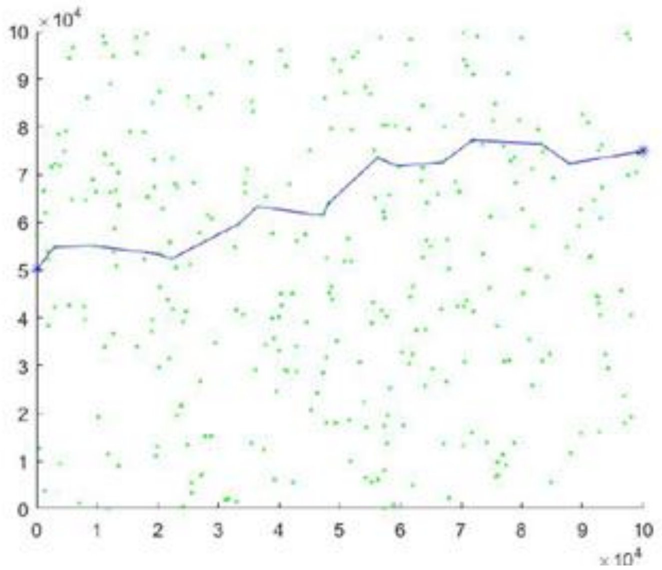

Figure 6 Flight route of data set 2 of problem 2

The trajectory obtained by our method is more convenient for trajectory tracking and control, with higher precision, better control quality and better searching speed. Constraint conditions in this paper can achieve the optimal result. Simulation and experiment verify the feasibility of the method in this paper, the complexity is higher when calculating the radius of curvature.

3.5 Problem three

Objective function:

$$\min \sum_{i=1}^{N} S_i \text{, where } S_i=\sqrt{(x_i-x_{i-1})^2+(y_i-y_{i-1})^2+(z_i-z_{i-1})^2}$$

$$\min \sum_{i=1}^{N}(I(\varepsilon_{H_i}\le\alpha_2,\varepsilon_{V_i}\le\alpha_1)+I(\varepsilon_{V_i}\le\beta_1,\varepsilon_{H_i}\le\beta_2))$$

$$\max SP=1-FP$$

$$\begin{cases}\varepsilon_{V_0}=0,\varepsilon_{H_0}=0\\ \varepsilon_{V_{i+1}}=\varepsilon_{V_i}+\delta S_i\\ \varepsilon_{H_{i+1}}=\varepsilon_{H_i}+\delta S_i\\ FP=FP+0.2*SP\end{cases}$$

Constraints:

$$\frac{\partial\varepsilon_{V_i}}{\partial S_i}=\delta$$

$$\frac{\partial\varepsilon_{H_i}}{\partial S_i}=\delta$$

$$\sum_{i=0}^{N}\varepsilon_{V_i}<\theta$$

$$\sum_{i=0}^{N}\varepsilon_{H_i}<\theta$$

If $\varepsilon_{H_i}\le\alpha_2,\varepsilon_{V_i}\le\alpha_1$ then $\varepsilon_{V_{i+1}}=0$

If $\varepsilon_{V_i}\le\beta_1,\varepsilon_{H_i}\le\beta_2$, then $\varepsilon_{H_{i+1}}=0$

Since there are two correct directions, the node in which direction the problem occurs is likely to lose contact due to the error of this, and this phenomenon may occur at the next correction point, so the statistical probability is relatively complex. Therefore, a parameter with positive correlation with probability is proposed to replace the actual probability. The actual probability calculation is hard. There is one more condition for problem 3 compared with problem 1. Therefore problem 3 becomes a three-objective optimization problem, adding another objective function on the basis of problem 1. Assume that the initial failure probability is 0, if failed every time, the worst situation will lead to being disable to correction. Occurrence of failure probability is measured, so failure probability * 0.2 = failure probability + success probability. Probability of success =1- probability of failure. Since it is very complicated to define the probability of failure, the probability of failure here is not the actual probability of failure, but a parameter that is positively correlated with the probability of failure, which can well describe the change of probability. In order to ensure that the probability of success can be well described, the number of successive nodes should be counted first, so that the real probability can be calculated by Monte Carlo simulation.

3.6 The results of problem 3

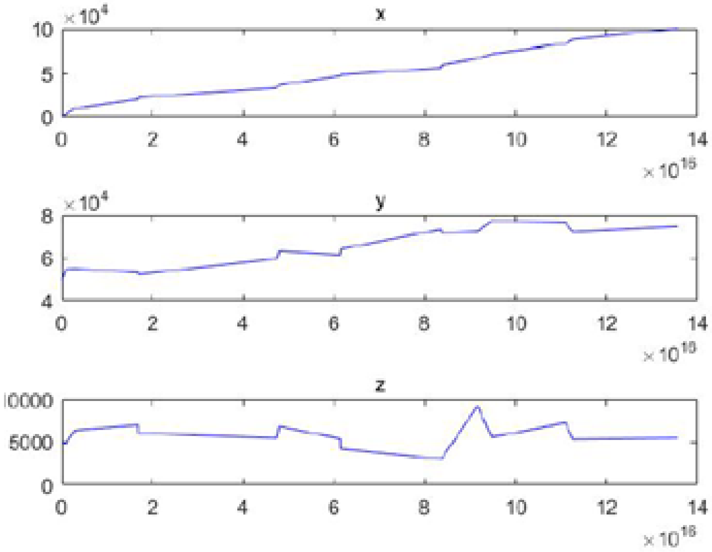

Figure 7 Monte Carlo simulation under three dimensions of problem 3

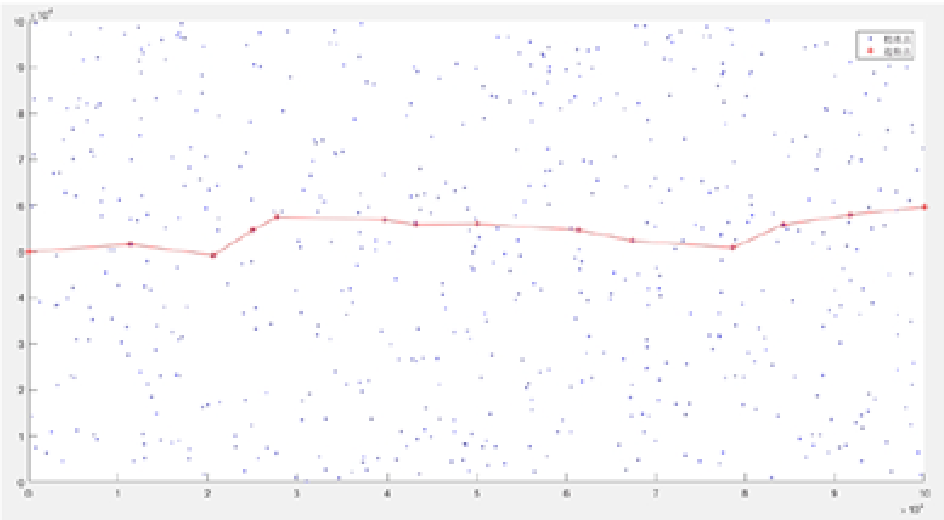

Figure 8 Flight route of problem 3

4. Conclusion

One of the advantages of the model is that the model has a solid and reliable mathematical foundation. The model is easy to implement. The model makes the number of correction errors smaller. In addition, the established model method is not only simple and easy to operate, but also is applicable in real life situations.

Disadvantages of the model are less than the number of advantages of the model. One of the disadvantages is that the model is built on the basis of genetic algorithm. This algorithm belonging to multi-objective programming problem is most likely used for biological genetic modeling. Moreover, due to the complexity of practical problems, the assumptions of the model are too ideal. However, the model in this article is good for flight route modeling under certain constraints.

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