An Approach of ACARS Trajectory Reconstruction Based on Adaptive Cubic Spline Interpolation

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Abstract. Trajectory reconstruction is one of the key technologies to achieve flight trajectory and ensure the safety of flight. Aircraft Communication Addressing and Reporting System (ACARS) is a digital data link system that transmits short messages by radio or satellite between aircraft and ground station. In this paper, an approach based on adaptive cubic spline interpolation is proposed for ACARS trajectory reconstruction. The ACARS data points of different flight phases are reconstructed, and the appropriate trajectory curve is obtained. This approach is verified in simulation platform by using true flight historical data. Experimental results show that this approach obtained better smoothness and lower error precision than that of traditional trajectory reconstruction algorithm, especially in take-off and landing phases. Improving the degree of cure smoothing and decreasing its error are helpful to the accurate trajectory and position of the flight, which provides a guarantee for the safe operation of the air traffic.

Keywords: Flight safety · ACARS · Trajectory reconstruction · Adaptive · Cubic spline

1 Introduction

Aircraft Communication Addressing and Reporting System (ACARS) is a data link system which is widely used in international civil aviation. It is used to monitor the aircraft in real time. Since Malaysia Airlines MH370 incident occurred in March 8, 2014, in order to ensure the safe operation of air transport, the International Civil Aviation Organization (ICAO) and the aviation industry attached great importance to trajectory the global flight by using the ACARS data [1].

In the era of rapid development of communication network, the core of the next generation aviation transportation system-Next Generation Air Transportation System (NextGen) is Trajectory-based Operational [2, 3]. Trajectory reconstruction is one of the core technologies of the Trajectory-based Operational. In the operation and management of the trajectory, the trajectory reconstruction can accurately predict the current position and future position of the civil aviation aircraft in high density airspace, and solve the Airspace utilization and improve the flight safety and operational

efficiency of the civil aviation aircraft [4, 5]. It is a technical problem that needs to be solved urgently at present.

Besada, et al. presented a method of air traffic control trajectory reconstruction for sensor and trajectory performance evaluation [6]. Sotiriou et al. studied an adaptive time-series probabilistic framework for 4-D trajectory conformance monitoring [7]. The trajectory reconstruction of aircraft was studied in Nanjing University of Aeronautics & Astronautics, but they had some defects. Wang used the traditional cubic spline interpolation and linear interpolation to reconstruct the trajectory [8]. The smoothness and accuracy of the trajectory obtained was not good through two algorithms. Lu did not launch a specific study of different flight stages (take-off, cruise and landing) [9].

This paper proposes adaptive cubic spline algorithm which uses ACARS data link technology to carry on the trajectory reconstruction, improve the accuracy of trajectory, reduce the estimation error, and achieve the purpose of flight trajectory.

2   Adaptive Cubic Spline Interpolation Algorithm

In order to ensure the real-time performance of the aircraft, it is needed to fit the accurate trajectory of the aircraft. Therefore, we propose an adaptive cubic spline interpolation based ACARS trajectory reconstruction algorithm, which can be used to reconstruct the real time flight path of the aircraft. The basic idea of this method is that the number and the initial value of spline are given by the algorithm. The initial node vector is used to construct B spline basis functions and the coefficients of the basis functions are obtained. Then the spline function values are obtained by the least square method to solve the B spline curve equation. Then we calculate the error of the spline function and the original data. If it is less than the specified error, the trajectory can be constructed to meet the requirements, if the error is greater than the specified error, the initial value of the node is changed or the number of the nodes is changed, and the operation is carried out until it meets the requirements [10, 11].

In the adaptive trajectory reconstruction, the initial value N is given, and the data points $\{t_i\}_{i=0}^{N}$ are constructed according to the message. These data points are within the range of [A, B], among them, $t_0 = A, t_N = B$. We select N − 1 random number $\{r_i\}_{i=1}^{N-1}, 0 < r_i < 1$. We can use the formula $t_i = r_i t_{i-1} + (1 - r_i)t_{i+1}$ $i = 1, \ldots, N - 1$ to get the monotonically increasing random sequence $\{t_i\}_{i=0}^{N}$. We take this sequence as the sequence of the spline. Solving tri-diagonal equations as follows.

$$\begin{pmatrix} -1 & 1-r_1 & & & \\ r_2 & -1 & 1-r_2 & & \\ & \ddots & \ddots & \ddots & \\ & & r_{N-2} & -1 & 1-r_{N-2} \\ & & & r_{N-1} & -1 \end{pmatrix} \begin{pmatrix} t_1 \\ t_2 \\ \vdots \\ t_{N-2} \\ t_{N-1} \end{pmatrix} = \begin{pmatrix} -r_1 A \\ 0 \\ \vdots \\ 0 \\ -(1-r_{N-1})B \end{pmatrix} \quad (1)$$

We construct the cubic B-spline by using the node vector, and determine whether the accuracy is up to the requirement. If the accuracy does not meet the requirements,

we select another set of random number and reconstruct the curve. In order to get the node vector with the specified accuracy, this process is repeated several times. If we do not meet the requirements at the number of nodes, the number of nodes will change (the number of nodes increased by 1 in turn). Then repeat the above process until the requirements are met [2, 12].

The main steps of the algorithm are as follows:

Step 0 (initialization): (a) Original points $\{x_i, y_i, z_i\}_{i=1}^{w}$. (b) Number of nodes N. (c) Under the fixed length, nodes were selected randomly Num times (Num represents the maximum value possible). (d) Specified accuracy e.

Step 1. Selecting random number $\{r_i\}_{i=1}^{N-1}$. If min $r \to 0$ or max $r \to 1$, we select the random number.

Step 2. Using formula 1 to get the internal node $\{t_i\}_{i=1}^{N-1}$.

Step 3. If $|t_{i+1} - t_i| < \theta, \theta = 1.0 \times 10^{-4}$, We remove a node.

Step 4. Node normalization.

Step 5. Construct cubic B-spline basis function.

Step 6. The ACARS data parameter values are brought into the basis function, and the coefficient matrix is obtained.

$$\begin{cases} N_{i,0}(t) = \begin{cases} 1 & if\ t_i \le t < t_{i+1} \\ 0 & other \end{cases} \\ N_{i,k}(t) = \frac{(t-t_i)N_{i,k-1}(t)}{t_{i+k}-t_i} + \frac{(t_{i+k+1}-t)N_{i+1,k-1}(t)}{t_{i+k+1}-t_{i+1}} & k > 0 \\ 0/0 = 0 \end{cases} \tag{2}$$

Step 7. Solving equations

$$\begin{pmatrix} y_1 \\ \vdots \\ y_w \end{pmatrix} = \begin{pmatrix} N_{0,k}(x_1) & \cdots & N_{n,k}(x_1) \\ \vdots & \vdots & \vdots \\ N_{0,k}(x_w) & \cdots & N_{n,k}(x_1) \end{pmatrix} \begin{pmatrix} \beta_0 \\ \vdots \\ \beta_n \end{pmatrix} + \delta \tag{3}$$

Step 8. Determine whether the error is less than precision. Yes, step 10; No, step 9.

Step 9. $num = num + 1$. If $num < Num$, to perform step 1; if $num \ge Num$, so $N = N + 1, num = 1$.

Step 10. End of program.

3   Experiment and Result Analysis

In this paper, the experimental system is using a PC machine and MATLAB simulation software for data processing. In order to ensure the reliability of the experiment, the original data of this paper originates from the domestic real flight data of an airline [13, 14].

The experimental scheme of trajectory reconstruction is shown in Fig. 1.

In order to carry on the comparative analysis, the experiment uses three kinds of flight path methods, as follows.
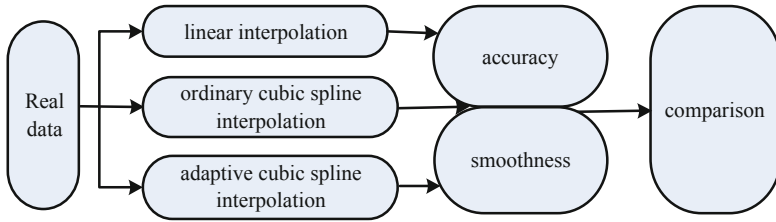
Fig. 1. Experimental scheme of trajectory reconstruction

- Adaptive cubic spline interpolation
- Linear interpolation
- Ordinary cubic spline interpolation

The trajectory of the three methods are compared and analyzed.

Using the historical flight data, three methods are used to reconstruct the trajectory, and the results are shown in Fig. 2.
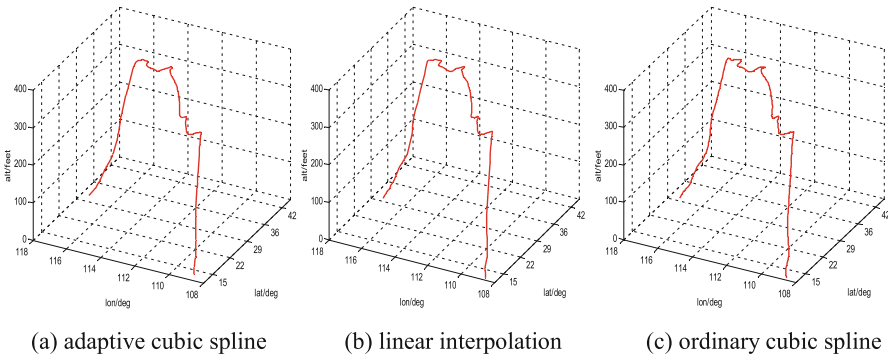

(a) adaptive cubic spline (b) linear interpolation (c) ordinary cubic spline

Fig. 2. Reconstructed trajectory

As shown in Fig. 2(a), (b) and (c), in the reconstruction of ACARS trajectory, adaptive cubic spline has a higher accuracy than ordinary cubic spline interpolation and linear interpolation. In the smoothness of the trajectory, the trajectory has an advantage by adopting the adaptive cubic spline function, and it is more flexible in the curve reconstruction.

In order to explain the effect of interpolation function and the accuracy of each flight phase, we have to make the interpolation operation for each stage of the flight (take off, cruise and landing) [15, 16].

1. Take-off phase

In the take-off phase, the flight path of the three methods is shown in Fig. 3.
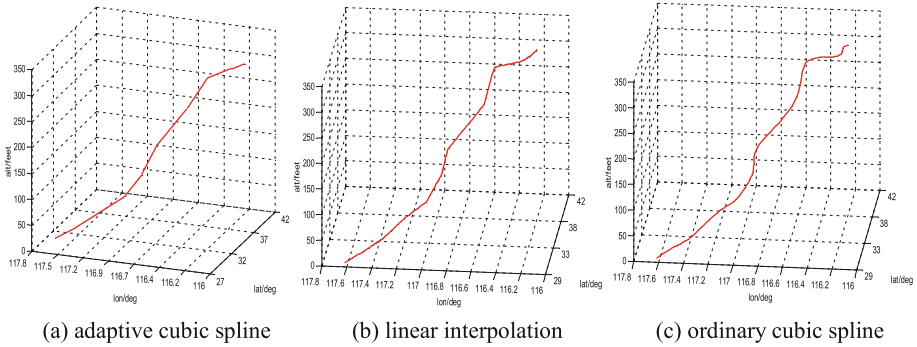
(a) adaptive cubic spline   (b) linear interpolation   (c) ordinary cubic spline

Fig. 3. Trajectory in the take-off stage

As shown in Fig. 3(a), (b) and (c), the smoothness of ordinary cubic spline is significantly better than the linear interpolation in the take-off stage, but obviously worse than the adaptive cubic spline.

2. Cruise phase

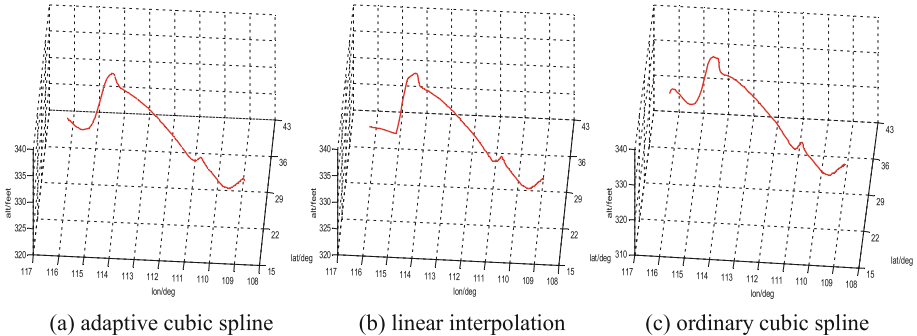In the cruise phase, the flight path of the three methods is shown in Fig. 4.

(a) adaptive cubic spline   (b) linear interpolation   (c) ordinary cubic spline

Fig. 4. Trajectory in the cruise stage

As shown in Fig. 4(a), (b) and (c), due to the original trajectory data is relatively flat, the effect of three methods is similar in the cruise phase. However, in the relatively large fluctuations of the trajectory stage, the smoothness of the adaptive cubic spline curve is better than the ordinary cubic spline curve, and the ordinary cubic spline curve is better than the linear interpolation curve.

3. Landing phase

In the landing phase, the flight path of the three methods is shown in Fig. 5.

As shown in Fig. 5(a), (b) and (c), we can see that the smoothness of the cubic spline curve is still better than the linear interpolation curve in the landing phase of the
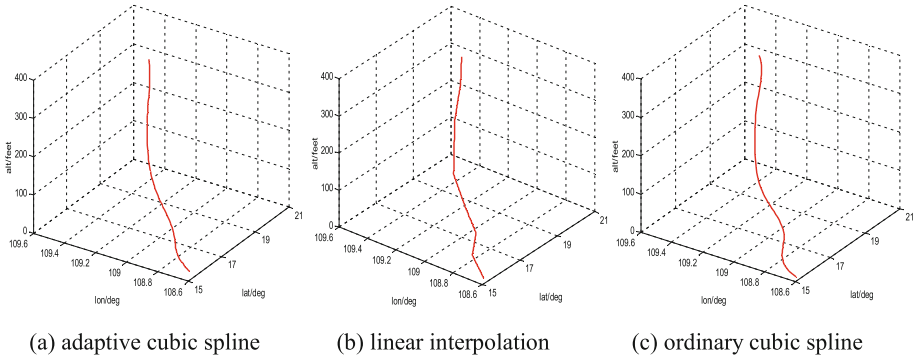
(a) adaptive cubic spline   (b) linear interpolation   (c) ordinary cubic spline

Fig. 5. Trajectory in the landing stage

trajectory, and the adaptive cubic spline curve is better than the ordinary cubic spline curve.

The smoothness of the trajectory fitting curve and the precision of the reconstructed trajectory are two important parameters in the trajectory of real-time monitoring applications. Through the analysis of the experimental results, this paper analyzes the smoothness of the trajectory fitting curve and the accuracy of the reconstructed trajectory.

Contrast the smoothness of the trajectory in the three stages:

- Due to the location of the data has a good stability in the cruise phase, results of the three methods are smooth. In the large deflection of the trajectory segment, the adaptive cubic spline interpolation is still relatively smooth.
- During take-off and landing stage, some of the changes in the technical indicators of the aircraft is relatively large (such as flight altitude, flight speed), resulting in a complex distribution of trajectory points. Compared with the other two interpolation methods, the reconstructed trajectory obtained by the adaptive cubic spline method has obvious advantages.

In order to get the precision of the reconstructed trajectory, the root mean square error (RMSE) is used as the criterion to evaluate the accuracy of the trajectory. The trajectory data is used as the reference value, and the accuracy of the trajectory is calculated by the three algorithms (see Table 1).

Table 1. Trajectory interpolation contrast experiment (%)

Error	Take-off stage			Cruise stage			Landing stage		
	a	o	l	a	o	l	a	o	l
Lat	1.04	10.9	17.5	0.05	0.43	0.61	0.49	4.78	19.5
Lon	0.16	0.81	1.57	0.28	0.80	1.08	0.12	0.43	1.09
Alt	0.27	0.88	1.53	0.42	1.37	2.06	0.13	0.40	0.88

Lat, Lon, Alt denote Latitude, Longitude, Altitude respectively.
l, o, a denote linear, ordinary and adaptive respectively.

From Table 1 we can reach the following conclusions.

- In the cruise phase, due to the flight data is relatively stable, the reconstruction of the trajectory does not show a greater difference in accuracy, the three methods have shown a better performance.
- Due to the irregular flight data, the accuracy of the cubic spline curve is still better than the ordinary cubic spline curve in the take-off and landing phases and the ordinary cubic spline curve is better than the linear interpolation curve.

The algorithm of this paper is different from others. According to the different trajectory curves, the distribution of nodes is not the same. In the large deflection, the distribution of nodes is relatively large, so that the error of the trajectory is small. In the small deflection, the distribution of nodes is relatively small. Under the premise of ensuring the accuracy, in order to improve the efficiency of the algorithm and ensure accurate trajectory of flights, the number of nodes is less as far as possible. Therefore, the experimental results show that the adaptive cubic spline algorithm has a good performance of the flight trajectory in the range of error allowed.

4 Conclusion

We get the better smoothness and higher accuracy of the trajectory by using the method, this method meets the International Civil Aviation Organization (ICAO) latest implementation of the global flight trajectory standards. By using the flight data transmitted by ACARS system to reconstruct the flight path, it can provide accurate flight information to the global flight trajectory, realize the accurate positioning of the flight, and provide guarantee for the safe operation of the air traffic.

In the actual flight, the flight time is relatively short, and the interval between the messages sent by ACARS is relatively long, so there are not many available trajectory points, so the accuracy of the reconstructed trajectory needs to be further improved. Due to the randomness of node selection in this method, the precision and time of the reconstructed trajectory can be better. Therefore, the selection and optimization of the node is the focus of the research in future.

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