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An Algorithm for Interpolating Ship Motion Vectors

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ABSTRACT: Interpolation of ship motion vectors is able to be used for estimating the lost ship AIS dynamic information, which is important for replaying marine accidents and for analysing marine traffic data. The previous methods can only interpolate ship's position, while not including ship's course and speed. In this paper, vector function is used to express the relationship between the ship's time and space coordinates, and the tangent of the vector function and its change rate are able to express physical characteristics of ship's course, speed and acceleration. The given AIS dynamic information can be applied to calculate the parameters of ship's vector function and then the interpolation model for ship motion vectors is developed to estimate the lost ship dynamic information at any given moment. Experiment results show that the ship motion vector function is able to depict the characteristics of ship motions accurately and the model can estimate not only the ship's position but also ship's course and speed at any given moment with limited differences.

1 INTRODUCTION

Since 2003, China has begun to deployed shore-based AIS stations, which gradually covers all key coastal waters as well as the important ports along China coastline. Now, the AIS reports collected by these AIS stations are widely used in marine traffic supervising, marine traffic statistics and marine accident investigations, and so on, by maritime safety authorities or port authorities.

According to the performance standards of ship borne Automatic Identification System, ship static information is broadcast every 6 minutes or when asked, and the minimum interval of broadcasting dynamic information reports is 2 seconds and the maximum is 3 minutes [1]. According to statistics in Shanghai [2], dynamic information of about 15% ships is not updated in 3 minutes, dynamic information of about 10% ships is not updated in 5 minutes, and dynamic information of about 5% ships is not updated in 15 minutes. There are two reasons contributed to this delay. One is that the deployment of base stations is not sensible, and another is that the crowded marine traffic like in port of Shanghai may result in AIS information transmission blocking. In consequence, it is necessary to develop a algorithm for interpolating ship AIS motion vectors to estimate the lost ship AIS reports when replaying marine traffic accidents or analysing the marine traffic with AIS reports collected by shore based AIS stations.

In recent years, the research on smoothing and recovering the trajectory of moving-objects has made abundant achievements. An Extended Kalman Filter (EKF) was proposed for the estimation of vessel states and further used for the prediction of vessel trajectories [3]. A data model of HCFMOST (History-Current-Future Moving Objects Spatio-Temporal) was presented and the trajectories of moving objectives were stimulated by using cubic Hermite interpolation [4]. These methods, however, could not restore or predict ship motion at any given time.

The curve-based model was presented to provide much more accurate trajectory [5]. A generalized trajectory interpolation model using parametric trajectory representations was proposed in [6]. Smooth trajectory tracking interpolation on a robot simulator and interpolation of mobile robot trajectory tracking control were presented in [7] and [8]. Piecewise cubic spline interpolation was used for restoring vessel track based on AIS Information in [9]. The 5th-order Runge-Kutta-Nystrom method was presented to interpolate ship positions for on-board navigation systems [10]. A spatiotemporal uncertainty model was proposed for interpolation of continuously changing data objects [11-12]. These methods are able to be used for smoothing trajectory, however, not for moving-objects' velocity and direction.

In order to depict the physical relationship between the time and space parameters of a ship, vector function is introduced in this paper, then ship motion vector function is constructed and interpolation model is set up. With given AIS report information, the parameters of ship motion vector interpolation model can be determined, and then the model can be used to estimate ship's position, course and speed at any given time.

This paper is organized as follows: Section 2 presents ship motion vector function. Section 3 introduces the model for interpolating ship motion vectors and the model's parameters is optimized. Section 4 describes the method calculate ship moving acceleration which is not reported by AIS. Section 5 demonstrates an experiment and related error analysis. Finally, conclusions are given in section 6.

2 SHIP MOTION VECTOR FUNCTION

Ships navigate in a two-dimensional Euclidean space. Let vector function $\boldsymbol{r}(\boldsymbol{t})$ be ship's motion vector function, then given time $\boldsymbol{t_0}$, radial vector $\boldsymbol{r}(\boldsymbol{t_0})=\{\boldsymbol{x}(\boldsymbol{t_0}),\boldsymbol{y}(\boldsymbol{t_0})\}$ can express ship's position. Tangent vector $\boldsymbol{r'}(\boldsymbol{t_0})=\{\boldsymbol{x'}(\boldsymbol{t_0}),\boldsymbol{y'}(\boldsymbol{t_0})\}$ can denote ship's speed and ship's course. Vector $\boldsymbol{r}(\boldsymbol{t_0})$ and vector $\boldsymbol{r'}(\boldsymbol{t_0})$ can depict ship's motion state, as shown in Fig 1.

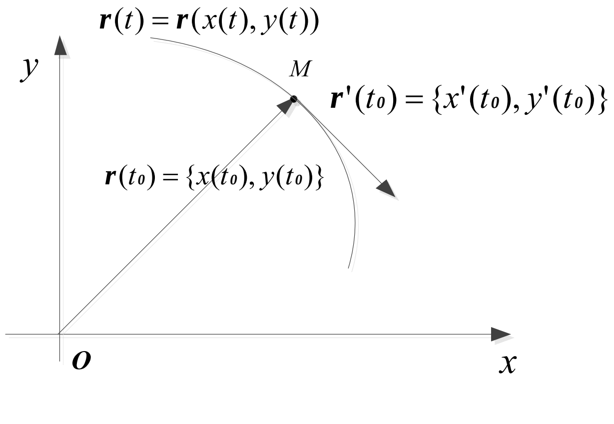

Figure 1. Vector function of ship movements

3 MODEL FOR INTERPOLATING SHIP MOTION VECTORS

Given vector function which indicates ship's movement, interpolation model for ship motion vectors is set up. Then the physical characteristics between ship and ship's speed, heading are analysed.

3.1 *Model for interpolating moving-object's trajectory*

In order to make sure that the model expresses moving-objects' motion vectors as accurate as possible, firstly, vector function must satisfy the given motion vectors of the moving-object. Secondly, the model for interpolating moving-object's motion vectors is set up. The model for interpolating moving-objects' motion vectors is defined as follows.

For any given adjacent time t_i and t_j $(t_i \le t_j)$ and their interval $[t_i, t_j]$, coordinate vector and high order coordinate vector of t_i and t_j are $\boldsymbol{r}^{(n)}(t_i) = \{x^{(n)}(t_i), y^{(n)}(t_i)\}$ and $\boldsymbol{r}^{(n)}(t_j) = \{x^{(n)}(t_j), y^{(n)}(t_j)\}$, $(n = 0,1,2,...)$ respectively, and vector function of the moving object at time t ($t \in [t_i, t_j]$) can be expressed by Equation (1).

$$\boldsymbol{r}(t) = \{x(t), y(t)\} = \{\sum_{k=0}^{2n+1} a_k t^k, \sum_{k=0}^{2n+1} b_k t^k\} \tag{1}$$

where a_k, b_k, $(k = 0,1,2,...,2n+1)$ should meet Equation (2) and (3).

$$\boldsymbol{r}^{(n)}(t = t_i) = \boldsymbol{r}_i^{(n)} \tag{2}$$

$$\boldsymbol{r}^{(n)}(t = t_j) = \boldsymbol{r}_j^{(n)} \tag{3}$$

3.2 *Parameters of the model for interpolating ship's motion vectors*

In order to develop the model for interpolating ship motion vectors, the parameters $\boldsymbol{a_k}$, $\boldsymbol{b_k}$ of the interpolation model is to be determined in this section.

According to Equation (1), the order of vector function at any time t is depended on the value of $\boldsymbol{k}$ which is further depended on the value of $\boldsymbol{n}$. if $\boldsymbol{n} = 1$, then $\boldsymbol{k} = 3$, and if $\boldsymbol{n} = 2$, then $\boldsymbol{k} = 5$. Assuming at time $\boldsymbol{t_i}$ and $\boldsymbol{t_j}$, ship dynamic information includes position, course $\boldsymbol{C}$ and speed $\boldsymbol{v}$. When $\boldsymbol{n} = 1$, then each order of ship radial vector functions are expressed by Equation (4), (5) ,(6) and (7).

$$\boldsymbol{r}_i = \{x(t_i), y(t_i)\} \tag{4}$$

$$\boldsymbol{r}_j = \{x(t_j), y(t_j)\} \tag{5}$$

$$\boldsymbol{r}_i' = \{\cos(C_{t_i}) v_{t_i}, \sin(C_{t_i}) v_{t_i}\} \tag{6}$$

$$\boldsymbol{r}_j{}' = \{\cos(C_{t_j})v_{t_j}, \sin(C_{t_j})v_{t_j}\} \tag{7}$$

Among them, $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ show the radial vectors of ship at time $\boldsymbol{t}_i$ and $\boldsymbol{t}_j$ respectively, $\boldsymbol{r}'_i$ and $\boldsymbol{r}'_j$ show the velocity vectors of ship at time $\boldsymbol{t}_i$ and $\boldsymbol{t}_j$ respectively .

According to Equation (2), the parameter vector $\boldsymbol{a}_k$ can be achieved by Equation (8).

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -3 & 3 & -2 & -1 \\ 2 & -2 & 1 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{r_i} \\ \boldsymbol{r_j} \\ (t_j - t_i)\boldsymbol{r}_i{}' \\ (t_j - t_i)\boldsymbol{r_j}{}' \end{bmatrix} \tag{8}$$

Similarly, if $\boldsymbol{n}$ = 2, suppose $\boldsymbol{r}_i''$ and $\boldsymbol{r}_j''$ show the acceleration vectors of ship at time $\boldsymbol{t}_i$ and $\boldsymbol{t}_j$ respectively, the parameter vector $\boldsymbol{a}_k$ can be achieved by Equation (9)

$$\begin{bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0 \\ -10 & 10 & -6 & -4 & -1.5 & 0.5 \\ 15 & -15 & 8 & 7 & 1.5 & -1 \\ -6 & 6 & -3 & -3 & -0.5 & 0.5 \end{bmatrix} \begin{bmatrix} \boldsymbol{r_i} \\ \boldsymbol{r_j} \\ (t_j - t_i)\boldsymbol{r_i}{}' \\ (t_j - t_i)\boldsymbol{r_j}{}' \\ (t_j - t_i)^2\boldsymbol{r_i}{}'' \\ (t_j - t_i)^2\boldsymbol{r_j}{}'' \end{bmatrix} \tag{9}$$

the parameter vector $\boldsymbol{b}_k$ can also be achieved in the similar way.

From Equation (8) and (9), it is obviously that the values of the model's parameters are directly related to the distance of the given two motion nodes. In order to acquire ideal parameters and accurate model, the condition as Equation (10) shows should be satisfied before interpolating [13].

$$\max\left(\left|\boldsymbol{r}_i{}'\right|, \left|\boldsymbol{r}_j{}'\right|\right) \le 3\left|\boldsymbol{r}(t_i) - \boldsymbol{r}(t_j)\right| \tag{10}$$

3.3 *Connection conditions of the model for interpolating ship motion vectors*

In section 3.1 and 3.2, this paper develops the model for interpolating ship motion vectors between two given adjacent ship motion vectors. The trajectory near the joint of two segments which are formed by the given ship motion vectors and interpolated motion vectors, however, is not certain to be smooth. In order to construct a trajectory satisfying with C^2 [14] standard, two adjacent interpolated trajectories should be connected in C^2 at the connection point. Therefore, it is necessary to discuss the connection conditions of two adjacent interpolated trajectories. Su Buqing has presented its necessary and sufficient conditions in [14].

Given two intervals $[t_{j-1}, t_j]$ and $[t_j, t_{j+1}]$, interpolated trajectories of ship are $\boldsymbol{r_1}(t)$ and $\boldsymbol{r_2}(t)$, the sufficient and necessary conditions for meeting C^2 standard at the connection point t_j is expressed by Equation (11) .

$$\begin{cases} \boldsymbol{r_1}(t_j) = \boldsymbol{r_2}(t_j) \\ \boldsymbol{r_1}{}'(t_j) = \alpha\boldsymbol{r_2}{}'(t_j) \\ \boldsymbol{r_1}{}''(t_j) = \alpha^2\boldsymbol{r_2}{}''(t_j) + \beta\boldsymbol{r_2}{}'(t_j) \end{cases} \tag{11}$$

where α and β are constants, and usually, α and β have two kinds of values. One case is $\alpha = 1$ and $\beta = 0$, which is suitable for equal time interval motion vectors, otherwise interpolated trajectory will be shaking. Another case is $\alpha = \left|\boldsymbol{r_1}(t_{j-1}) - \boldsymbol{r_1}(t_j)\right| / \left|\boldsymbol{r_2}(t_j) - \boldsymbol{r_2}(t_{j+1})\right|$ and $\beta = 0$, which is suitable for parametric interpolation. The latter kind of values is used in this paper.

4 CALCULATION OF SHIP'S ACCELERATION

To develop a more accurate model for interpolate ship motion vectors, it is necessary to introduce high order parameters, i.e. acceleration of ship motion, into the model as Equation (9) shows. However, AIS does not report ship's acceleration right now, so it's necessary to develop a method to estimate it with neighbouring ship motion vectors.

Obviously, the closer between the estimated acceleration and actual acceleration, the more accurate the interpolation model is. Greater time difference between two adjacent motion nodes will lead to greater error. Therefore, more time-adjacent motion nodes will be selected to calculate the acceleration at a given node.

For example, given three ship motion nodes at time $\boldsymbol{t}_{i-1}$, $\boldsymbol{t}_i$, and $\boldsymbol{t}_{i+1}$ as shown in Fig. 2, difference of time $\boldsymbol{\Delta t}_{i-1}=\boldsymbol{t}_i-\boldsymbol{t}_{i-1}$, $\boldsymbol{\Delta t}_i=\boldsymbol{t}_{i+1}-\boldsymbol{t}_i$ and difference of speed $\boldsymbol{\Delta v}_{i-1}=\boldsymbol{v}_i-\boldsymbol{v}_{i-1}$, $\boldsymbol{\Delta v}_i=\boldsymbol{v}_{i+1}-\boldsymbol{v}_i$, if $\boldsymbol{\Delta t}_i > \boldsymbol{\Delta t}_{i-1}$, then $a_i = \frac{\Delta \upsilon_{i-1}}{\Delta t_{i-1}}$ and if $\boldsymbol{\Delta t}_i < \boldsymbol{\Delta t}_{i-1}$, then $a_i = \frac{\Delta \upsilon_i}{\Delta t_i}$, where $\boldsymbol{a}_i$ denotes ship moving acceleration at time $\boldsymbol{t}_i$.

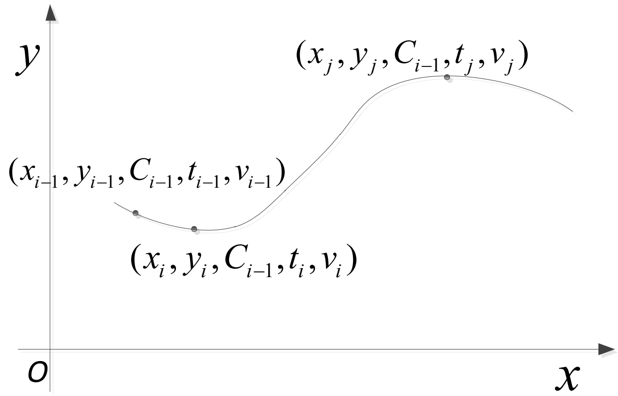

Figure 2. Distribution of ship's adjacent nodes

5 EXPERIMENT

AIS dynamic reports are used to verify the effectiveness of the model introduced in this paper. For better demonstration, this paper uses the AIS dynamic reports, totally 1400 reports or motion vectors in this paper, of a ship with MMSI of 412049010 from 1426 to 2159 local time on January 31, 2013, when she navigated near the mouth of Yangzte River where the traffic is very crowded and ship need change course or speed frequently. Fig 3 shows the trajectory constructed with the given AIS dynamic reports.

The experimental steps are as follows.

1 Extracted Sampling nodes from ship's AIS dynamic information as the interpolation nodes, as shown in Fig 4.
2 Set up the model for interpolating ship's motion vectors with determined sampling points. The steps to interpolate ship motion vectors are shown in table 1.
  Interpolated trajectory is shown in Fig 5 while interpolated courses and speeds are shown in Fig 6. In order to analyze the differences between the estimated motion vectors and the observed motion vectors, the experiment estimates the motion vectors for the moments corresponding to each observed motion vectors.
3 Calculating differences of ship's position, speed and course between the estimated motion vectors and the corresponding observed vectors as shown in Fig. 8, 10, 12.

Table 1. Steps for interpolating ship motion vectors

step	actions
1	Construct ship motion vector sequence in time ascending order with ship AIS dynamic information records, and let counter i= 0.
2	the ith (if any), $(i+1)^{th}$, $(i+2)^{th}$, and $(i+3)^{th}$ (if any) motion vectors are selected.
3	The model for interpolation of vectors between the $(i+1)^{th}$ and $(i+2)^{th}$ motion vectors, is set up with given four motion vectors.
4	Interpolate all ship motion vectors between the $(i+1)^{th}$ and $(i+2)^{th}$ motion vectors with designated interval or strategy.
5	Update speed and acceleration of the $(i+2)^{th}$ motion vector, let $i=i+1$, if $i = n-2$, then quit, otherwise back to step 2, where n is the number of all given vectors.

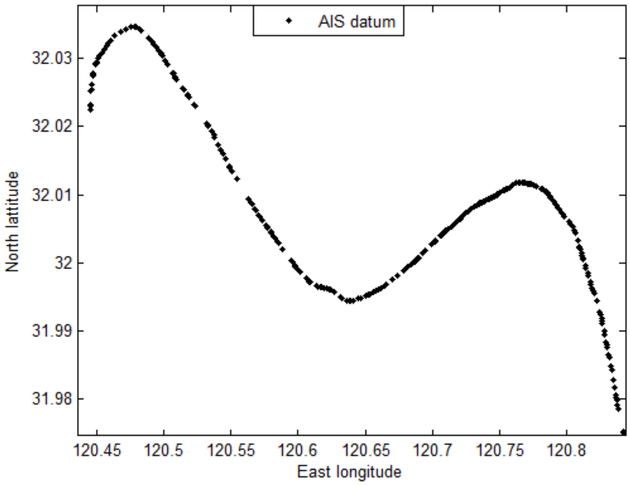

Figure 3. Motion nodes from ship's AIS data

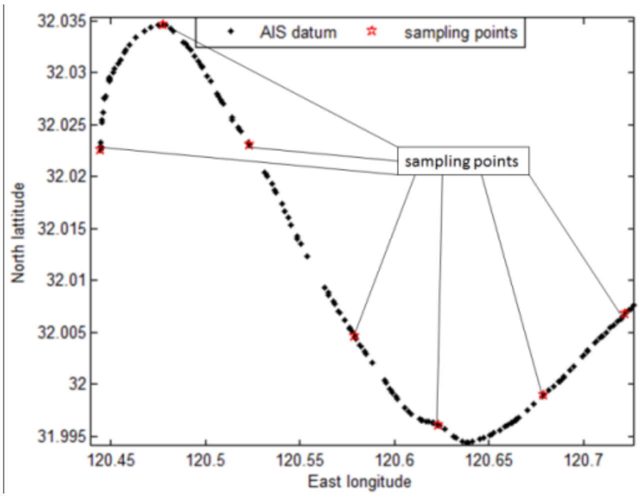

Figure 4 Sampling nodes from ship's AIS data

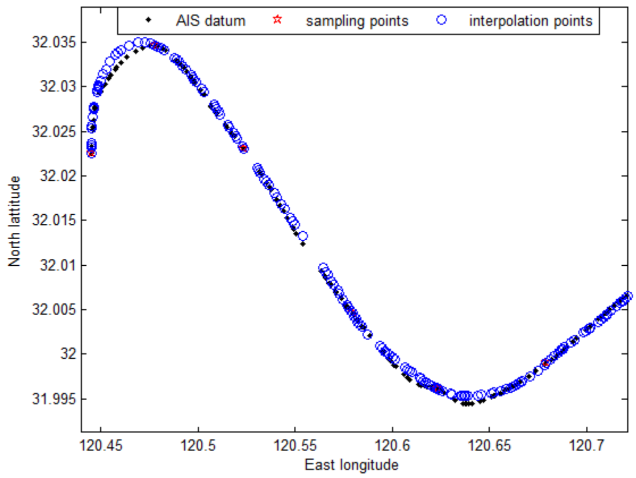

Figure 5. Observed trajectory and estimated trajectory

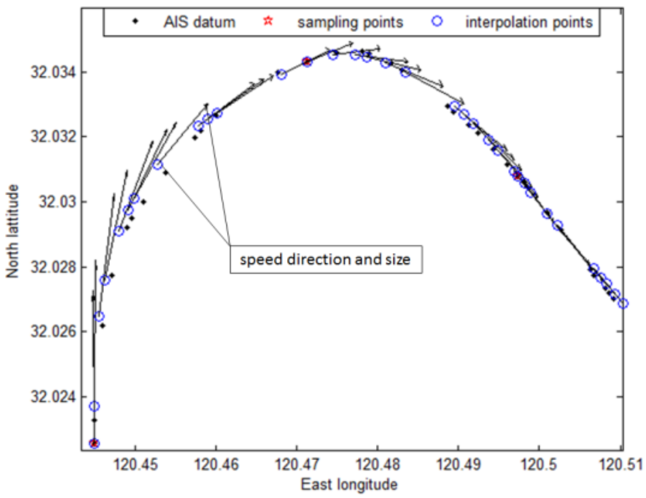

Figure 6. Interpolated velocity vectors

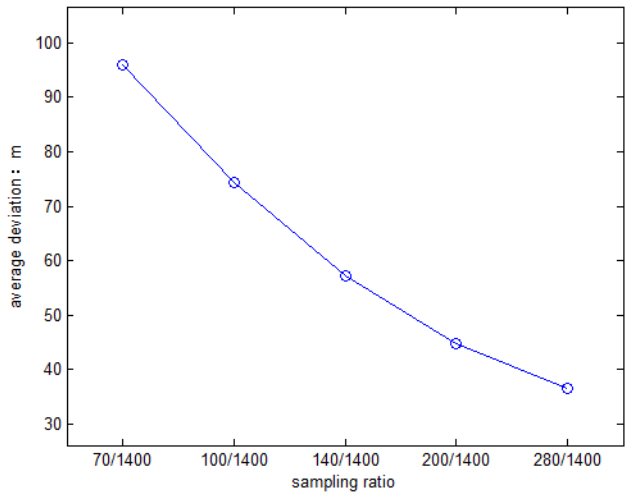

Figure 7. Average position differences under different sampling ratios

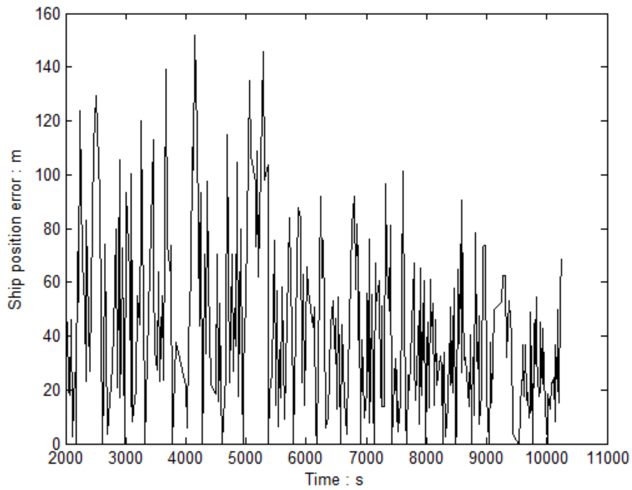

Figure 8. Position differences of sampling ratio 107/1400

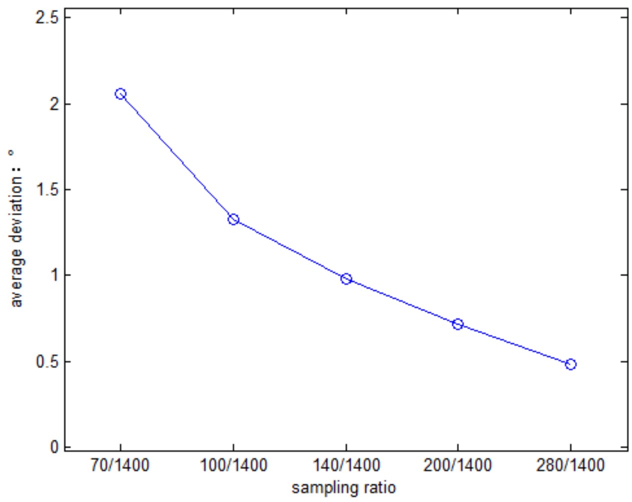

Figure 9. Average course differences under different sampling ratios

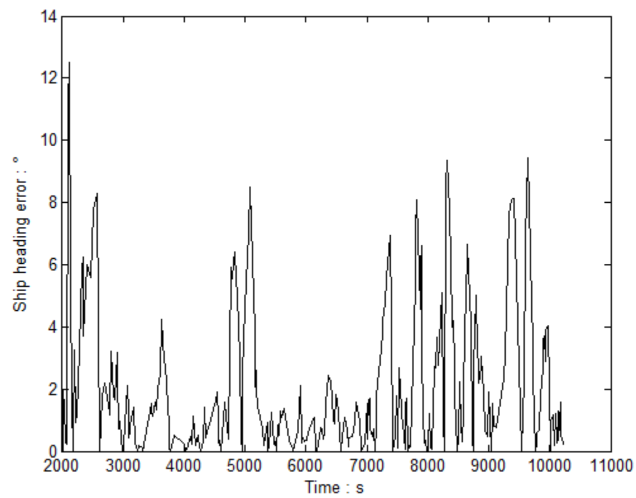

Figure 10. Course differences of sampling ratio 107/1400

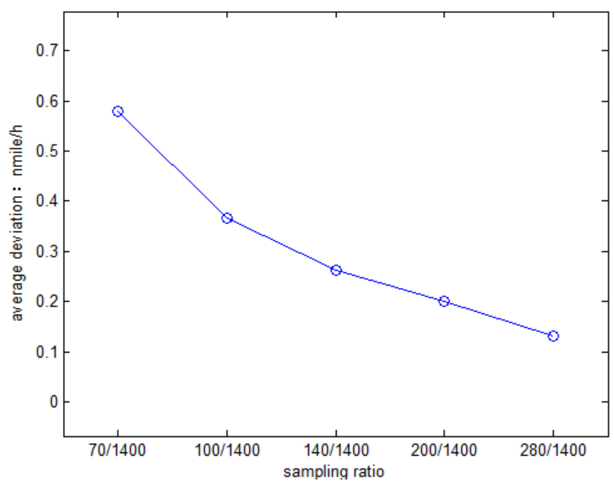

Figure 11. Average speed differences under different sampling ratios

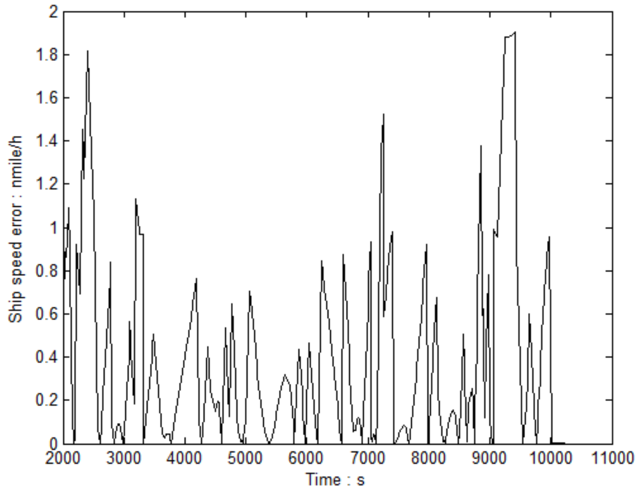

Figure 12. Speed differences of sampling ratio 107/1400

From the above charts, it's obvious that this algorithm is feasible and with increasing of sampling nodes, the differences between interpolated motion vectors and the observed motion vectors decreased significantly as shown in figure 7,9,11.

6 CONCLUSIONS

In this paper, vector function is introduced to express ship motion vectors, and based on it, the model and the algorithm for interpolating ship motion vectors are developed to estimate the lost ship AIS dynamic reports which often arise in crowded waters. Experiment results show that the estimated ship motion vectors are very close to the observed position, course and speed if the given observed motion vectors satisfied the introduced condition. Moreover, the more AIS dynamic reports are given, the closer the estimated value and observed value are.

The algorithm introduced in this paper can play a significant role when replaying the marine accidents or analysing the marine traffic relating to the waters where AIS report lost often occurs.

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