Data Map Characteristic in Aided Navigation

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Abstract - Both Terrain Aided Inertial Navigation Systems (TAINS) and Gravity Aided INS (GAINS) are sorted out with Data-map Aided INS (DAINS). The reliability of DAINS relies on the characteristic of the reference map. The relationship has been dealt with among the sensors’ sampling cycle, the sensors’ precision, the data-map precision and its statistical characteristics. In this way, the related parameters are decided. Through simulation, different vehicle velocities along the same track in a defined region make for different precisions. Some perfect results are obtained.

Key Words- Data map, aided navigation, Inertial navigation system

I. INTRODUCTION

To improve the precision and stability of Inertial Navigation System (INS), various integrated navigation systems are used in underwater vehicles. A number of them correct INS with external information such as Global Positioning System (GPS), Doppler Velocity Log (DVL) and so on. In many applications, these solutions are not satisfactory. Furthermore, reliance on external signals is not good due to jamming or spoofing\(^{[1-4]}\).

Another category of INS augmentation is based on map matching, called as Data-map Aided INS (DAINS). The geophysical data types in reference maps include bathymetric (terrain), magnetic, gravitational datum\(^{[2-4]}\). The map matching algorithms have been developed such as TERCOM, SITAN and so on. Their precisions rely on the precision of onboard sensors and reference map, etc.. It is also well known that a featureless map cannot be provided to accurately correct or update INS data.

A reference map is evaluated with many methods such as statistic feature and fractal dimension. Unfortunately, all of them are not relative to vehicle navigation status, while in fact the different results are corresponding to the different velocity even with the same reference map. In this paper, the relationship between map aided navigation performance and map statistic feature is constructed with its local statistic parameters and the onboard sampling cycle. As a result, the new parameters are more efficient than the old ones in simulation experiments.

II. MODEL OF DAINS

In the underwater DAINS, bathymetric, gravity anomaly, and geomagnetic data are used. Among them, the bathymetric technique is sophisticated with reliable sensors and high resolution maps. Other methods are different from it with different sensors and map’s resolution, etc., but their principles are the same.

Map matching is used to estimate the vehicle position, and its referenced data map can be defined as a two-dimensional data set \(A\).

\[
A = \{S(i,j) | (i,j) \in \Omega\}
\]

(1)

\(S(i,j)\) is the geophysical value on the position \((i, j)\). \((i, j)\) is the grid index in navigation area \(\Omega\).

\[
\Omega = \{(i,j) | 1 \leq i \leq M, 1 \leq j \leq N\}
\]

(2)

Its map scales, \(M\) and \(N\) are the maxima of the map grid along two coordinate axes respectively.

The data \(S(T_k)\), acquired from onboard sensors, are one-dimensional array with time sequence radix.

The estimation \(P_k\) is the position to satisfy the requirement of Eq.3.

\[
\max_{\delta} \{f(P_k, S(T_k))\}
\]

(3)

The function \(f(*)\) has different expressions by different algorithms.

III. DEFINITION OF DATA MAP LOCAL FEATURE

The DAINS precision, influenced by terrain feature, has been analyzed in Ref. 3. The map feature is described in frequency and space domains, with parameters such as standard deviation, kurtosis and skewness coefficients, fractal dimension, etc. In this paper, only spatial statistic feature is discussed.

A Statistical Feature of Data Map

Statistical features of data map are analyzed with standard deviation, kurtosis coefficient, skewness coefficient, slope grade and aspect and roughness, etc. Their definitions have been
given in Ref. 3. Here, only the first three parameters are listed.

$$\sigma_T = \frac{1}{M \times N - 1} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} (S_{i,j} - \bar{S})^2$$

(4)

$\sigma_T$ is standard deviation, which is used to represent the fluctuation of the reference map. $\bar{S}$ is the mean of the map, and $M \times N$ is its matrix scale.

$$C_e = \frac{1}{MN} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left( S_{i,j} - \bar{S} \right)^4 - 3$$

(5)

$C_e$ is kurtosis coefficient, which indicates the concentration around the mean of data map. The greater the value is, the greater the map convergence is, and vice versa.

$$C_s = \frac{1}{MN} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left( S_{i,j} - \bar{S} \right)^3$$

(6)

$C_s$ is the skewness coefficient, which indicates the symmetry of the data map. The greater the value is, the more symmetrical the map is.

Slope grade and aspect are used to describe the oblique of the three-dimensional surface at a local area. Roughness describes the tiny fluctuation of the surface.

All of the above statistical characteristics are fixed to the assigned data map. If they are used to evaluate a data map, its navigation ability is invariable to any vehicle in any status. Obviously, this kind of fixedness is not suitable.

B Statistical Feature of Data Map Based on Navigation

To evaluate the navigation ability of map matching, the characteristics of data map must be integrated with the vehicle status and the sensors’ precision. Based on this consideration, an universal criterion is established for DAINS to judge its reliability.

As a kind of vehicle status, the velocity is related to the sampling periods of its sensors, while data map has its own spatial periods based on the map grid. So the relationship is set up between signal sampling time sequence and spatial sampling period of two-dimensional data field.

$$\vec{H} = \Delta t \cdot \vec{V}$$

(7)

Here, $\Delta t$ is the signal sampling period; $\vec{V}$, as a vector, is the moving vehicle speed; $\vec{H}$, as the displacement vector, actually is the spatial sampling period of moving vehicles.

Compared with the grid width of data map and the spatial sampling period, the scale of data map is changed with $\vec{H}$. In Eq.1-3, the scale is an important factor, by which $\vec{H}$ can be used to get a new scale $(M', N')$ of the data map.

$$\begin{bmatrix} M' \\ N' \end{bmatrix} = \begin{bmatrix} \Delta_x & 0 \\ 0 & \Delta_y \end{bmatrix} \begin{bmatrix} M \\ N \end{bmatrix}$$

(8)

$\Delta_x$ and $\Delta_y$ are the widths of an unit grid (resolution in X and Y direction of data map); $\theta$ stands for the angle between vehicle moving direction and X.

Eq.4-6 can be translated into the forms as follows:

$$\sigma_T' = \frac{1}{M' \times N' - 1} \sum_{i=0}^{M'-1} \sum_{j=0}^{N'-1} (S_{i,j} - \bar{S})^2$$

(9)

$$C_e' = \frac{1}{M' \times N'} \sum_{i=0}^{M'-1} \sum_{j=0}^{N'-1} \left( S_{i,j} - \bar{S} \right)^4 - 3$$

(10)

$$C_s' = \frac{1}{M' \times N'} \sum_{i=0}^{M'-1} \sum_{j=0}^{N'-1} \left( S_{i,j} - \bar{S} \right)^3$$

(11)

Here, $i'$ and $j'$ are the indexes of new grid; $\sigma_T'$, $C_e'$ and $C_s'$ are dynamic standard deviation, dynamic kurtosis coefficient and skewness coefficient respectively.

Furthermore, parameter $E$ is used to evaluate the difference between two-point values with specified sensors. It is defined as follows.

$$E = \frac{S_{i,j} - S_{k,l}}{\varepsilon}$$

(12)

Here, $\varepsilon$ is the sensor precision.

To judge the reliability of map-matching at one point, a local window is used. The Window width must be bigger than the error aroused by INS, and its center is the point to be evaluated. Then the window value can be calculated as follows.

$$E_{i,j} = \frac{S_{\text{max}} - S_{\text{min}}}{\varepsilon}$$

(13)

Subscripts $i$ and $j$ are the central position of the window; $S_{\text{max}}$ and $S_{\text{min}}$ indicate the maximum and minimum in the window respectively.

The change rate along a direction of one point $(i, j)$ can also be expressed as follows:
Here, \( \Delta = \Delta = \Delta \).

IV. SIMULATION AND RESULT ANALYSIS

A. Simulation

To verify the relationship between the above variants (\( \sigma^* T \), \( C^* e \), \( C^* s \), etc.) and the navigation precision, simulations are finished with various navigate speeds, gravity anomaly maps and bathymetric maps. Map matching algorithm is BITAN, which is one of the Improved SITAN algorithms\(^4\). The simulation conditions are listed in Table I.

Experiment factors are navigation speed, signal sampling period and data maps with different features. The statistics of each map are listed in Table II.

The values of navigation speed are 4, 10 and 18 knots. Navigation paths are along latitude direction. The navigation distance is 43.2 nautical miles; the signal sampling periods are 12, 24 and 60 seconds. The results are shown in Fig. 1.

B. Analysis of Simulation Results

1. According to the curves in the figures, parameters (\( C^* e \) and \( \sigma^* T \)) are related to the CEP (the Circle of Equal Probability). CEP decreases with the increase of them. Because of using spatial sampling period in the parameters, the ability of data map is distinguished. Especially, when \( C^* e \) is increased, CEP is decreased; match probability is increased.

2. Due to the small standard deviation in gravity anomaly map (map 5), navigation feature is submerged in the sensor noise, which leads to the failure of data matching.

V. CONCLUSION

The new statistical characteristics are associated with data map features, and vehicle moving status, which can represent the map matching ability. They are also the bases for switching data maps during real-time navigation, and offer reliability reference for data fusion to different aided navigation systems.
Fig. 1. Result of simulation

REFERENCES


