Study on Underwater Terrain Matching Positioning Based on the Integration of TERCOM and MCTM

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***Abstract*-Based on the current situation of underwater navigation, this paper presents an underwater topographic matching navigation method which is the integration of TERCOM and MCTM algorithm. First of all, we use the TERCOM to acquire a rough position of vehicle. Secondly, a search area is found according to TERCOM positioning result. The multi-contour matching algorithm is implemented in the area. The algorithm is based on the chain code. By means of the code technique, all of contours are coded. Then, each contour coded in the real-time terrain is matched with the corresponding background one. Each matched contour can provide a set of transformation parameters between the real-time terrain and the background. According to all of the transformation parameters acquired from different contour matches, a weighted average is adopted so as to acquire the accurate transformation parameters. Finally, By means of the final transformation parameters, the actual location of underwater vehicle is given out.**

I. INTRODUCTION

Underwater navigation based on seabed terrain matching is becoming a hot research topic recently [1][2][3][4]. In the navigation process, multibeam bathymetric system (MBS) can acquire the swath sounding data of seabed, and the seabed terrain can be expressed in form of terrain contour with MBS sounding data. When seabed is not very flat, the terrain matching based on the terrain contour is quite effective. There are several kinds of algorithms for underwater terrain matching, such as terrain contour matching (TERCOM), multi-contours terrain matching (MCTM) based on chain code and so on. TERCOM algorithm determines the vehicle position by computing the correlation of the surveying terrain sequence and the background terrain. TERCOM has its advantage in the computation velocity. However, the accuracy of the method is not high due to less redundancy and thus limits it's applications in precise underwater positioning. While MCTM based on chain code is a very well complement to TERCOM. By using rich redundancy matching information, MCTM has high precision and reliability in actual applications. Nevertheless, due to the computational complexity, the algorithm takes longer time in a region matching positioning. Thus, this paper presents a new algorithm which is the integration of TERCOM and MCTM so as to overcome the disadvantages of each other and get higher accuracy and reliability in underwater navigation.

II. PRINCIPLE INTERGRATION OF TERCOM AND MCTM

The thought of the integration algorithm of TERCOM and MCTM can be depicted as Fig. 1.

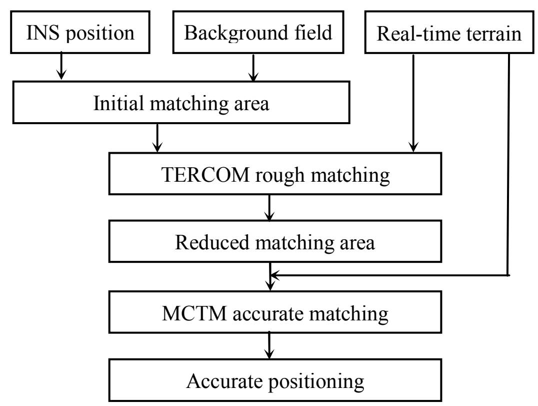

Figure 1. The framework of the presented algorithm

A. Terrain matching using TERCOM

Using TERCOM, the positioning is achieved by matching a real-time sounding sequence and the background terrain data in the scope provided by inertial navigation system (INS). During the matching process, there are three algorithms to be used for correlative analysis, which are cross-correlation (COR) algorithm, average absolute difference (MAD) algorithm and standard deviation (MSD) algorithm respectively, which are depicted as following [5].

$$COR(\tau_x ,\tau_y) = \frac{1}{L}\int_{-\frac{l}{2}}^{\frac{l}{2}} T_{ACQ}(x,y) * T_{ST}(x+\tau_x, y+\tau_y)dx \quad (1)$$

$$MAD(\tau_x,\tau_y) = \frac{1}{L}\int_{-\frac{l}{2}}^{\frac{l}{2}} T_{ACQ}(x,y) - T_{ST}(x+\tau_x, y+\tau_y)dx \quad (2)$$

$$MSD(\tau_x,\tau_y) = \frac{1}{L}\int_{-\frac{l}{2}}^{\frac{l}{2}} [T_{ACQ}(x,y) - T_{ST}(x+\tau_x, y+\tau_y)]^2 dx \quad (3)$$

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where, τ_x is the offset value in the direction to be parallel to *x*-axis, while τ_y is the offset value in the direction to be parallel to *y*-axis. T_{ACQ} is real-time height sequence measured by MBS, while T_{ST} is that stored in the background terrain database at the position ($x+\tau_x$, $y+\tau_y$). L is the matching length. In above correlative analysis, when COR becomes maximum, while both MAD and MSD become minimum, we think that the real-time observation sequence of seabed fulfills the best matching with the terrain background field at this time. The position of the real-time observation sequence is also that of the underwater vehicle.

Influenced by single matching sequence, the accuracy and reliability of TERCOM is limited. Thus we use two matching sequences to enhance the algorithm. Firstly, for each rectangle survey area, we choose the survey data along two diagonals as the matching sequences. Secondly, each matching sequence is used for matching with background TERCOM for compute the vehicle position, and the final result is the mean value of the two matching results.

TERCOM has the advantage in its velocity, while the disadvantage in its accuracy.

B. Terrain matching using MCTM

Through TERCOM match, we have a rough vehicle position. Thus we can choose a search area for the MCTM matching. The center of the matching area is the TERCOM matching location adding twice length of TERCOM positioning accuracy. This area is defined as the new matching area, in which MCTM will be executed.

The MCTM is based on the chain code which is proposed by Li et al [6]. The contour coding is to represent the shape of the contours with an integer sequence $\{a_j \in (0, 1, 2, \ldots, 7)\}$, depending on the relative position of the current grid point of the contour with respect to the previous one. The relationship between the relative position of two points and corresponding integer is shown in the Fig. 2. After above processing, the chain code of a contour needs to be further smoothed by Gaussian filter so as to remove the noise

In MCTM matching, there are two kinds of contour matching ways, namely the open contour matching and the closed contour matching. In the open contour matching, if there exists two open contours A and B, which have the same height h, the contour A is represented by a M-point chain code $\{a_i\}$, and contour B is represented by a N points chain code $\{b_i\}$. The best matching segment, which includes n points between contours A and B ($\min(M, N)$ / 2 $\le$n $\le \min(M, N)$) , can be found by computing the correlation D_{kr}

7	0	1
6	Current Point	2
5	4	3

Figure 2. The chain code method which based on the relationship between the current point and the next point

$$D_{kl}=\frac{1}{n}\sum_{j=1}^{n-1}\cos\frac{\pi}{4}(a_{k+j}-b_{l+j}) \tag{4}$$

here D_{kl} can be thought to be the mean squared error of two signals. The cosine function ensures D_{kl} <=1, and D_{kl} = 1 when there is a perfect match. In order to identify the location of best matching between contours A and B, an n-point segment from the contour A at index k is slide over contour B. The similarity function C_{AB}, which is used for reflecting matching degrees, is defined as (5).

$$C_{AB}=\max\{D_{ol}\} \quad 0 \le 1 \le N \tag{5}$$

Since an open contour A in the survey area is always a segment of the corresponding contour B in the reference area and its chain code have less points relative to B. Thus, for each contour A which has the height h in the survey image, what we do is to calculate the similarity function C_{AB} between A and each contour B which has the same height h in the reference image. The contour which has the biggest C_{AB} is considered to be the matching contour of A in the reference image.

While for a closed contour pair, the useful information is the shape attributes in the matching. The closed contour matching has been discussed by many researchers. There are a lot of methods to be proposed, such as the calculation of the first and second invariant moments proposed by Hu [7]. However, in our study, the data resolutions are different between the surveying data and the reference data, which often cause the obvious shape changes of the closed contour. Thus, we should only choose the most robust closed contour for the matching.

In our work, we use parameters L, D_1 and D_2, which are used for depicting the shape attribute of the matching contour. L is the length of the contour. D_1 is the maximum distance between the centroid of the closed contour and the points of the contour. D_2 is the minimum distance between the centroid of the closed contour and the points of the contour. During the matching process, each of the closed contours in the surveying image is compared with each of the closed contours in the reference image. The contour pairs are accepted as candidate set if the relative differences of their shape attributes are less than some threshold (30% in our study).This step reduces the searching scope of the prospective matching contours to several contours. Subsequently, the chain code algorithm described above is adopted for choosing the most suitable contour as the match contour.

C. Registration parameters estimation

The geometrical deformation between the reference contour image and surveying contour image is assumed to be a rigid transformation in our case. Rigid transformation preserves the distance between any two points in the domain of transformation. There does not exist scale change in a rigid transformation. In the navigation application, the rigid transformation can be expressed as

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = s\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{6}$$

where (x', y') is the new coordinates of point (x, y) after the transformation which caused by the underwater vehicles motion, the scaling factor s equals 1 in the navigation process. θ corresponds to the horizontal rotation angle between the surveying coordinate frame and the background or reference coordinate frame. θ is often caused by the gyro survey error, which is a small angle generally. (Δx, Δy) is the translations parameters along the two orthogonal directions respectively. The original points of the Cartesian coordinate systems are the centers of the images to be registered. x-axis is in the horizontal direction. y-axis is in the vertical direction.

After the registrations, we have a number of contour matching pairs, each pair can be used to calculate a set of transformation parameters(Δx, Δy).So if we have N pairs of matching contours, N-group transformation parameters can be gotten. Among these matching pairs, some ones may exist in them and decrease the matching accuracy. The median filter is adopted in the elimination of mismatching pairs. The parameters, which are far away from the median to some threshold (such as 1σ), will be thought to be false transformation parameters. After removing the mismatch pairs, the final estimate of the transformation parameter is given out by weighted average. In our research, we consider the contour pair which has longer length is more credible. That means a contour with long length has larger weight value relative the short one. For open contours, if the maximum length of the surveying open contour is L_{max}, then the corresponding weight p_i of each open contour pairs C_i is L_i/ L_{max}, where L_i is the survey contour's length of the open contour match pair. For a closed contour, the weight is given by the similar rule, but L_{max} is changed as the maximum length of the contour, correspondingly, L_i is the surveying contour's length.

III. EXPERIMENTS AND ANALYSIS

The data used for the experiments is measured by MBS at the FuChun River in Zhejiang Province, China. The surveying area is a quadrate riverbed with 3 km × 7 km. The mean, maximum and minimum depth are 8 m, 10m and 6 m respectively. The reference contour image of the area is showed in Fig. 3. Three experiments are implemented to test the effect of the method mentioned above.

Figure 3. The reference contour image which is used as background data

TABLE I
MATCHING RESULTS UNDER DIFFERENT DIAGONAL LENGTH

Length of diagonal /m	Error in x direction/m		Error in y direction/m		RMS /m
	Max.	mean	Max.	mean	
400	162	35	118	23	42
800	89	15	56	11	18

In experiment 1, we only use TERCOM. Firstly, two groups of rectangles are chosen as survey areas. For the first group, the diagonal length of the area is bout 400 m, while for the second group, the diagonal length is bout 600m. After that, we execute TERCOM to them. The matching results are shown in TABLE I.

TABLE I shows that the reliability of the algorithm is sensitive to the diagonal length, which has higher performance than the short one when the diagonal length is long. This is easy to understand since the longer the diagonal is, the richer the computation data is. However, the longer data will takes longer time in actual data acquisition.

In experiment 2, the surveying data and reference data are have different resolution. The survey data used is the rarefying the reference data. The resolution of the reference topographic data is 10 m × 10 m, while 50 m × 50 m for surveying data. Different diagonal length is chosen for the matching. The results are shown in Table II According to these parameters in Table II, we can find that the reliability of the algorithm is quite sensitive to the data resolution. The RMS grows immediately when the data resolution decreases.

We also implement the match by MCTM algorithm. Both the background data and the surveying data have same resolution and the size of matching area is 1 km×1 km. The matching result is shown in Table III.

In order to explain the sensitivity of the algorithm, different data resolutions are adopted. The resolution of survey data is 10 m × 10 m, while 15 m × 15 m, 20 m × 20 m and 50 m × 50 m for surveying data respectively. Using these data, the matching positioning work is done, and the corresponding results are shown in Table IV.

TABLE II
RESULTS OF TERCOM WITH DIFFERENT DATA RESOLUTION

Length of diagonal/m	Resolution /m	Error in x direction/m		Error in y direction/m		RMS /m
		Max.	mean	Max.	mean	
400	50×50	452	313	374	297	431
800	10×10	214	167	265	199	259

TABLE III
MATCHING RESULTS FROM MCTM

Resolution /m	Error in x direction/m		Error in y direction/m		RMS /m
	Max.	mean	Max.	mean	
5×5	0	0	0	0	0
10×10	0	0	0	0	0
20×20	153	112	167	158	193
30×30	297	214	614	479	524

TABLE Ⅳ

RESULT OF THE CONTOUR REGISTRATION WITH DIFFERENT DATA RESOLUTIONS

Data resolution of Surveying/m	Error in x direction/m		Error in y direction/m		RMS /m
	Max.	mean	Max.	mean	
15×15	92	77	96	71	104
20×20	294	179	212	127	219
50×50	592	392	612	377	543

TABLE Ⅴ

RESULT OF INTEGRATION ALGORITHM

Data resolution of Surveying/m	Error in x direction/m		Error in y direction/m		RMS /m
	Max.	mean	Max.	mean	
15×15	85	73	96	69	101
20×20	241	155	236	136	206
50×50	335	213	297	201	292

In experiment 3, we adopt the integration algorithm for the matching positioning. Firstly, we use TERCOM to get the rough position of the underwater vehicle. After that, a searching radius is determined according to the accuracy of TERCOM. Since our aim is to find an area where the vehicle is there, we should choose a radius value which is much bigger than the maximum error of TERCOM. In our case, the searching radius is defined as 1 km. Then we implement MCTM in the searching area with the survey data, and the corresponding result is shown in Table V.

From Tab. V, we can see that the integration algorithm works well when there is a resolution difference between the survey data and background data. Because the redundancy contour matching information is used, the matching accuracy and reliability are improved relative to single TERCOM. While since the scope of the background is reduced, the consuming time of MCTM will be decreased relative to that in whole background. Besides, the result of TERCOM can be used in the MCTM process as a validation for error elimination, and thus improve the accuracy and reliability of the algorithm.

IV. CONCLUSIONS AND SUGGESTIONS

The underwater navigation method based on the integration of TERCOM and MCTM mentioned in this paper has higher accuracy and reliability relative to TERCOM, and have faster velocity in data processing relative to MCTM, which provides a new way to fulfill underwater navigation. The experiment results also prove above conclusions.

A problem should be paid more attention that the influence of data resolution for the matching. The matching accuracy and velocity should be considered in the choice of the data resolution. Generally, we suggest that small size grid in complex seabed is adopted, while larger size grid in flat seabed.

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