Research on navigation for underwater unmanned vehicle based on dynamic gray filtering method

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Abstract. According to the problem of large platform noise and external disturbance influence and the data may have outliers for UUV navigation, a dynamic grey filtering method based on fractional order operator is proposed. This method does not require prior knowledge and noise statistical properties of UUV system while establishing a dynamic grey model based on fractional operator according to navigation data. The deviation between the grey prediction value and the next navigation sample value is calculated and the data is fused according to the deviation to realize the real-time filtering. The simulation results show that the method is effective and feasible.

1 Introduction

The most effective carrier for underwater information transmission is acoustic wave. Acoustic navigation technology plays an important role in Unmanned Underwater Vehicle(UUV) navigation [1,2]. However, the environment of UUV is very complex, and the underwater acoustic received signal is disturbed by both the ocean environment and the platform itself, navigation results may inevitably have outliers [3]. It is necessary to remove outliers that may exist in navigation results to improve the accuracy of acoustic navigation system.

The commonly used methods of removing outliers include Kalman filtering and Median filtering. Kalman filter is a linear optimal filter, But the limitation of Kalman filtering lies in requiring accurate mathematical models and noise statistics of known systems [4,5]. UUV has strong nonlinearity and large model uncertainty while complex ocean noise is not always known [6], which limits the use of Kalman filter. The median filter is a linear smoothing filter, which has obvious effect on accidental random interference, but the filtering results for periodic interference and noise are poor [7]. To remove the possible outliers in the navigation results, a dynamic gray filter is proposed to process the UUV navigation data. The filter does not need the prior knowledge of UUV system and the statistical characteristics of noise while establishing a dynamic grey model based on fractional order operator according to the navigation data samples. The deviation between the grey prediction value and the next shooting navigation sample value is calculated, and the data fusion is made according to the deviation, which

increases the ability of removing outliers of the filtering results.

2 The principle of dynamic grey filter

The following is the basic idea of using the gray filter to track UUV trajectory: Firstly, the gray model(GM) based on fractional order operator is established by the first N navigation data measured by sensors $\{y_1, y_2, \dots, y_N\}$. Then, the estimated value $\hat{y}_{N+1}$ of the N+1 time is calculated according to the mode, and the deviation $e = |\hat{y}_{N+1} - \tilde{y}_N|$ between $\hat{y}_{N+1}$ and the sampling navigation data $\tilde{y}_{N+1}$ of N+1 time is obtained. Finally, data fusion is carried out according to the deviation e, and the data after fusion are used as the navigation data measured by sensors of the N+1 time.

The expression of data fusion is

$$x_N = \omega_1 \tilde{y}_N + \omega_2 \hat{y}_N \quad (1)$$

where ω_1 and ω_2 are the weighted coefficients coefficient, and $\omega_1 + \omega_2 = 1$, $\omega_1 \geq 0$, $\omega_2 \geq 0$. Then data model will be carried out metabolism. Remove y_1 at the first moment, and y_{N+1} of N+1 time. and new data sequence $\{y_2, y_3, \dots, y_N, y_{N+1}\}$ will be obtained.

Updating the parameters of the grey mode and the data at N+2 time can be filtered. Such recursive algorithm can get real-time filtering results. The flow of grey filtering is shown in Fig.1.

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Fig. 1. Dynamic grey filtering process.

3 Dynamic grey model based on fractional order operator

Grey prediction model is a modeling method based on differential fitting and grey generating function. By mining and sorting out the original data, this method seeks its changing law and weakens the randomness of the objective system with complex representation and discrete data [8]. In the GM model, the differential equation based on the 1-AGO generated sequence obtained from the original sequence is denoted as GM (n, N). Where n represents the order of differential equations, and N represents the number of variables involved. The following are the principle and building steps of gray model based on fractional order operator.

Step1: Record the original data sequence as

$$X^{(0)} = \{X^{(0)}(1), X^{(0)}(2), \dots, X^{(0)}(N)\} \quad (2)$$

Step2: The r order accumulating generation operation sequences $X^{(r)}$ is generated by the r order accumulating generation of the original data sequence

$$X^{(r)} = \{X^{(r)}(1), X^{(r)}(2), \dots, X^{(r)}(N)\} \quad (3)$$

where

$$X^{(r)}(k) = \sum_{i=1}^k \frac{\Gamma(r+k-i)}{\Gamma(k-i+1)\Gamma(r)} X^{(0)}(i), k=1, 2, \dots, N$$

Γ is gamma function and $\Gamma(x) = \int_0^{+\infty} e^{-t} t^{x-1} dt$

Step3: the average sequence $Z^{(r)}$ is obtained by averaging the sequences $X^{(r)}$, and $Z^{(r)}$ is

$$Z^{(r)} = \{Z^{(r)}(2), Z^{(r)}(3), \dots, Z^{(r)}(N)\} \quad (4)$$

where

$$Z^{(r)}(k) = \frac{X^{(r)}(k) + X^{(r)}(k-1)}{2}, k=2, 3, \dots, N$$

Step4: Similar to accumulation, the r order reducing generating sequences $X^{(-r)}$ is generated by the r order reducing generation of the original data sequence

$$X^{(-r)} = \{X^{(-r)}(1), X^{(-r)}(2), \dots, X^{(-r)}(N)\} \quad (5)$$

where

$$X^{(-r)}(k) = \sum_{i=0}^{k-1} (-1)^i \frac{\Gamma(r+1)}{\Gamma(i+1)\Gamma(r-i+1)} X^{(0)}(k-i), k=1, 2, \dots, N$$

Step5: Build fractional order operator GM(1,1). $Z^{(r)}$ is used as the modeling data, the fractional order operator GM(1,1) can be obtained

$$\frac{dX^{(r)}(k)}{dN} + aZ^{(r)}(k) = b \quad (6)$$

where a and b is undetermined coefficient. $[a, b]^T = (B^T B)^{-1} B^T Y_N$ can be obtained by the least squares method, and where

$$Y = \begin{bmatrix} x^{(r-1)}(2) \\ x^{(r-1)}(3) \\ \vdots \\ x^{(r-1)}(N) \end{bmatrix}, \quad B = \begin{bmatrix} -Z^{(r)}(2) & 1 \\ -Z^{(r)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(r)}(N) & 1 \end{bmatrix}$$

The solution of the equation (6) is

$$\hat{X}^{(r)}(k) = \left(X^{(0)}(1) - \frac{b}{a} \right) \times e^{-a(k-1)} + \frac{b}{a}, \quad k=2, 3, \dots, N \quad (7)$$

Step6: Forecast the data of N+1 time.

According to formula (7), the estimated value of $X^{(r)}$ at N+1 time is $\hat{X}^{(r)}(N+1)$. For the original sequence $X^{(0)}$, the r order accumulating generation operation sequences $X^{(r)}$ and the r order reducing generating sequences $X^{(-r)}$, $X^{(0)} = (X^{(r)})^{(-r)} = (X^{(-r)})^{(r)}$ can be obtained [9]. Then, the predicted data for the N+1 time is

$$\hat{X}^{(0)}(N+1) = (\hat{X}^{(r)})^{(-r)}(N+1) = \sum_{i=0}^N (-1)^i \frac{\Gamma(r+1)}{\Gamma(i+1)\Gamma(r-i+1)} \hat{X}^{(r)}(N+1) \quad (8)$$

Step7: dynamic filtering

GM(1,1) filtering belongs to static filtering while the track of UUV is constantly changing. With the increase of data, the significance of initial data for GM(1,1) is reduced. If the initial data is used for long-term filtering, the filtering result will become worse. Therefore, trajectory dynamic information is introduced to reflect the motion state of UUV in real time. The method of building real time dynamic filtering is to remove $X^{(0)}(1)$ and add $X^{(0)}(N+1)$ in the sequence. The new original sequence is constructed as

$$X_{new}^{(0)} = \{X^{(0)}(2), X^{(0)}(3), \dots, X^{(0)}(N+1)\} \quad (9)$$

4 Simulations

The simulation condition: UUV moves along the 30 degree direction in a uniform linear motion at 5m/s, and the depth of UUV motion is constant. UUV obtains synchronous acoustic navigation data every 10 seconds, and the trajectory of UUV is shown in Fig3. From Fig3, we can see that there are 3 obvious outliers in the original navigation data. Fig.4 is the error distribution map of the original navigation data in Fig.3.

Fig. 2. UUV trajectory.

Fig. 3. Navigation error distribution.

Fig. 4. Navigation error distribution after dynamic grey filtering.

The original measurement data are divided into x-direction and Y-direction for dynamic gray filtering, classical CV model Kalman filtering and median filtering respectively.

Fig. 5. Navigation error distribution after Kalman filtering (noise is stronger compared to Fig.6).

Fig. 6. navigation error distribution after Kalman filtering.

The filtered results are shown in Fig.4, Fig.5, Fig.6 and Fig.7. Fig.4 is a dynamic grey filter. Fig.5 and Fig.6 are Kalman filters with different noise statistics, and compared with noise in Fig.6, Fig.5 has strong noise. Fig.7 is a Median filter. Compared with Kalman filter

and median filter, dynamic Grey filter is more effective in eliminating outliers from navigation data and it has the advantage of not requiring prior knowledge and noise statistics. The filtering result of Kalman filter is influenced by noise statistics, and outliers have great influence on the stability of Kalman filter system. Median filter has a certain filtering effect on accidental random interference, but the filtering effect on periodic noise and interference is poor.

Removing the outliers the filtered data of Fig. 4, Fig.5 and Fig.7, the mean square error of filtered data in X and Y directions is calculated, and the mean square error is shown in Table 1. As can be seen from Table 1, dynamic grey filtering can not only eliminate outliers effectively in navigation data, but also have certain filtering effect on periodic noise and interference.

Table 1. Mean square error (without outliers)

Mean square	X/m	Y/m
error		
Original data	3	3
Grey filtering	2.445	2.533
Kalman filtering	2.823	2.745
Median filtering	2.862	2.895

Fig. 7. Navigation error distribution after Median filtering.

5 Conclusions

In this paper, a dynamic gray filtering method of UUV navigation position information based on fractional order operator is proposed. The method achieves effective filtering of UUV tracks through dynamic grey prediction and data fusion and has the advantage of not

knowing the prior knowledge of UUV system. The simulation results show that the method is simple and effective and has strong ability of outliers elimination. It can improve the accuracy of acoustic navigation system effectively.

This work was supported by The National Key Research and Development Program of China (2017YFC0306900); Stable Supporting Fund of Acoustic Science and Technology Laboratory; Technical Basic Scientific Research Program (JSJL2016604B003); Open fund by Qingdao National Laboratory for Marine Science and Technology (QNL20160RP0102).

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