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Application of Modified Kalman Filtering Restraining Outliers Based on Orthogonality of Innovation to Track Tester

Zhang Xinchun and Cui Ximin
College of Geoscience and Surveying Engineering
China University of Mining and Technology Beijing
Beijing 100083, China
1051905834@qq.com

Yan Dongkun
Beijing Ming Ji Network Culture Co., Ltd

***Abstract* - In the process of application of Kalman filtering, the outlier observations are important factors influencing the filtering effect. When outliers appears in the observed values, it can destroy the Kalman filtering information features and make the Kalman filtering estimate inaccurately. To solve the problem that the accuracy and stability of inertial inspection system of railway track geometry state decreasing induced by the outliers of GPS, a new method based on orthogonality of innovation was proposed to process the data. This method detected whether there are outliers in the data of GPS by judging the orthogonality of innovation,while combining GPS Dilution of Precision. This method assigns an activation function as the weight to each element of measurement, which can keep the orthogonal properties of the innovation sequence and the outliers can be detected and corrected. The testing results show that it can detect the outliers effectively in practice and obtain ten times improvement of inspection accuracy.**

Index Terms - Inertial Satellite Navigation System; Dilution of Precision; Kalman filtering; innovation; orthogonality

I. INTRODUCTION

With the rapid growth of national economy, transportation industry of railway tracks has gained rapid development. In recent years, with the speed acceleration of ordinary railway lines and a large number of high-speed lines laying, the requirement for comfort of rails is gradually increasing, thus the laying of rails, high-speed and precise detection of rails in daily maintenance are becoming more and more important [1]. Inertia detection system of track geometry status based on inertial/satellite integrated navigation system has high measurement accuracy, fast measurement speed, but the satellite signal are susceptible to voltage signal of contact line interference and guardrail barrier, leading to the emerge of outliers, as a result of which, the position and posture accuracy of the inertial/satellite integrated navigation system is reduced, affecting the measurement precision of orbital parameters. Kalman outliers method based on orthogonality of innovation proposed in literature [2] determines whether any outliers in the measurement emerge or not by judging whether there is loss of orthogonality innovation or not, and carry out weighted limit in the measurement of outliers, but the article did not study outliers algorithm of multiple input multiple output systems. On the basis of literature [2], literature [3] provides outliers identification and correction method GPS, suitable for the SINS/GPS integrated navigation system, but does not consider the DOP value of satellite signal, leading to the inaccurate judgment of satellite signal outliers. This paper, based on this, with the introduction of satellite positioning DOP value, enhances the judgment accuracy of satellite signal outliers, improves the precision of Inertia detection system of track geometry status.

II. INERTIA DETECTION SYSTEM OF TRACK GEOMETRY STATUS

A.Geometry Status Detector of Absolute Orbit

Geometry status detector of absolute orbit with high precision robot total station, tilt sensor and speed sensor as core data collector, by translocation with CPIII ControlNet data, obtains ride comfort index such as rail gauge, alignment, high and low, level, distortion, at the same time can calculate the deviation of orbit plane, elevation and the design value. The precision of measuring instrument is high, but the measurement method is complex, each measurement needs precise adjustment and free station and orientation, working efficiency is relatively low [4-5].

B.Inertia Detection System of Track Geometry Status

Inertia detection system of track geometry status based on inertial navigation technology, has mature application in the domestic large track inspection car, but the requirement of inertial devices precision is higher, the system cost is relatively high. Therefore, the combination of inertial navigation system with the existing carrier of track geometry detector, development of new Inertia detection system of track geometry status with low cost, high precision, high efficiency, suitable for high-speed railway in our country is the trend of the development in the future [6-7]. The key technology of system are for modeling and compensation of inertial device error, multi-sensor information fusion and the development of inertial measurement platform for railway inspection.

Contact line is high voltage transmission line for pantograph flow, set up along the zigzag over the rail in electrified railway. It is made up of supporting device, positioning device, contact suspension, pillar and foundation. SINS/GPS integrated navigation system is applicable to the railway line of not large railway tunnel, but the GPS satellite

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signal are highly susceptible to interference, in order to get higher accuracy, detection of GPS outliers and selection of correction algorithm is particularly important.

III DISCRIMINATING PRINCIPLE OF ORTHOGONALITY OF INNOVATION OUTLIERS VALUE

Using the following equation of linear discrete system [8-10]:

$$\boldsymbol{x}_k = \boldsymbol{F}_{k,k-1}\boldsymbol{x}_{k-1} + \boldsymbol{G}^{\mathrm{w}}{}_{k-1}\boldsymbol{w}_{k-1} \tag{1}$$

$$Z_k = \boldsymbol{H}_k\boldsymbol{x}_k + \boldsymbol{v}_k \tag{2}$$

In equation: $\boldsymbol{x}_k \in \mathbf{R}^n$ is state variable; $\boldsymbol{F}_{k,k-1} \in \mathbf{R}^{n\times n}$ is state transfer matrix; $\boldsymbol{G}^{\mathrm{w}}{}_{k-1} \in \mathbf{R}^{n\times l}$ is process noise matrix; $Z_k \in \mathbf{R}^m$ is measurement variables; $\boldsymbol{H}_k \in \mathbf{R}^{m\times n}$ is measurement matrix; $\boldsymbol{w}_{k-1} \in \mathbf{R}^l$, $\boldsymbol{v}_k \in \mathbf{R}^m$ are process noise and measurement noise variables.

Assume $\boldsymbol{w}_{k-1}$ and $\boldsymbol{v}_{k-1}$ are zero mean AWGN, satisfies

$$\begin{cases} E\left[\boldsymbol{w}_k\right] = 0, \quad E\left[\boldsymbol{w}_k\boldsymbol{w}_j^{\mathrm{T}}\right] = \boldsymbol{Q}_k\delta_{kj} \\ E\left[\boldsymbol{v}_k\right] = 0, \quad E\left[\boldsymbol{v}_k\boldsymbol{v}_j^{\mathrm{T}}\right] = \boldsymbol{R}_k\delta_{kj} \\ E\left[\boldsymbol{w}_k\boldsymbol{v}_j^{\mathrm{T}}\right] = \mathbf{0} \end{cases} \tag{3}$$

In equation: $\boldsymbol{Q}_k \in \mathbf{R}^{l\times l}$ is process noise covariance matrices, assume is nonnegative definite matrix; $\boldsymbol{R}_k \in \mathbf{R}^{m\times m}$ is measurement noise covariance matrices, assume is negative definite matrix.

Discrete fundamental equation Kalman[11-12]

$$\hat{\boldsymbol{x}}_{k/k-1} = \boldsymbol{\Phi}_{k/k-1}\hat{\boldsymbol{x}}_{k-1} \tag{4}$$

$$\boldsymbol{P}_{k/k-1} = \boldsymbol{\Phi}_{k/k-1}\boldsymbol{P}_{k-1}\boldsymbol{\Phi}^{\mathrm{T}}_{k/k-1} + \boldsymbol{G}^{\mathrm{w}}_{k-1}\boldsymbol{Q}_{k-1}\left(\boldsymbol{G}^{\mathrm{w}}_{k-1}\right)^{\mathrm{T}} \tag{5}$$

$$\hat{\boldsymbol{x}}_k = \hat{\boldsymbol{x}}_{k/k-1} + \boldsymbol{K}_k\boldsymbol{e}_k \tag{6}$$

$$\boldsymbol{e}_k = Z_k - \boldsymbol{H}_k\hat{\boldsymbol{x}}_{k/k-1} \tag{7}$$

$$\boldsymbol{K}_k = \boldsymbol{P}_{k/k-1}\boldsymbol{H}_k^{\mathrm{T}}(\boldsymbol{H}_k\boldsymbol{P}_{k/k-1}\boldsymbol{H}_k^{\mathrm{T}} + \boldsymbol{R}_k)^{-1} \tag{8}$$

$$\boldsymbol{P}_k = (\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H}_k)\boldsymbol{P}_{k/k-1}(\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H}_k)^{\mathrm{T}} + \boldsymbol{K}_k\boldsymbol{R}_k\boldsymbol{K}_k^{\mathrm{T}} \tag{9}$$

In equation (7), $\boldsymbol{e}_k$ is innovation. It can be seen from the type (6) state estimation $\hat{\boldsymbol{x}}_k$ will be linearized by innovation through the filter gain. As a result, when the measurement Z_k is not outlier, innovation $\boldsymbol{e}_k$ will correct revision state estimation; when measurement Z_k produces outliers, innovation $\boldsymbol{e}_k$ loses orthogonality, abnormal $\boldsymbol{e}_k$ will revise $\hat{\boldsymbol{x}}_{k/k-1}$, which is a one-step prediction of system status t_k , resulting in state estimation deviation and reducing the precision of the state variables.

Using innovation orthogonality properties; under the condition of abnormal orthogonality, judge at this time measurement emerges outlier [13-16]. The innovation can be expressed as:

$$\boldsymbol{e}_k = Z_k - \widehat{Z}_k \tag{10}$$

In equation $\widehat{Z}_k = \boldsymbol{H}_k\hat{\boldsymbol{x}}_{k/k-1}$ is optimal estimate of measurement Z_k .

According to the nature of innovation orthogonality:

$$E\left[Z_kZ_k^{\mathrm{T}}\right] = E\left[\boldsymbol{e}_k\boldsymbol{e}_k^{\mathrm{T}}\right] + E\left[\widehat{Z}_k\widehat{Z}_k^{\mathrm{T}}\right] \tag{11}$$

Solve formula (11) :

$$E\left[Z_kZ_k^{\mathrm{T}}\right] = \boldsymbol{H}_k\boldsymbol{P}_{k/k-1}\boldsymbol{H}_k^{\mathrm{T}} + \boldsymbol{R}_k + \boldsymbol{H}_k\hat{\boldsymbol{x}}_{k/k-1}\hat{\boldsymbol{x}}_{k/k-1}^{\mathrm{T}}\boldsymbol{H}_k^{\mathrm{T}} \tag{12}$$

In equation R_k is measurement noise covariance matrix, is used to represent credibility of measurement information.

Diagonal element of measurement signal noise variance matrix R_k is observation credibility of satellite positioning system.

$$R_k = diag\left\{R_1{}^2; R_2{}^2; \ldots R_i{}^2; \ldots R_m{}^2\right\} \tag{13}$$

In the equation R_i is credibility of the i observed quantity, m means a total of m observed quantities.

Reliability of observed quantity of satellite positioning system is proportional to the satellite signal DOP value. Satellite signal DOP value consists of GDOP (Geometry DOP, Geometry dilution of precision) and PDOP (Position DOP, location dilution of precision), HDOP (Horizontal DOP, Horizontal coordinate dilution of precision), VDOP (Vertical DOP, Vertical coordinate dilution of precision) and TDOP (Time clock offset, Time dilution of precision), etc, the smaller the DOP is, the higher precision is. Noise variance measurement R_i and the DOP value have the following relationship [17-19].

$$R_i = N_iDOP_i + R_{i0} \tag{14}$$

In equation, N_i is scaling factor of satellite positioning system signal precision and the signal DOP value, R_{i0} is adjustment amount for noise measurement, the above values can be adjusted according to actual condition.

Bring equation(13),equation(14) into equation(12)

$$E\left[Z_kZ_k^{\mathrm{T}}\right] = \boldsymbol{H}_k\boldsymbol{P}_{k/k-1}\boldsymbol{H}_k^{\mathrm{T}} + \begin{bmatrix} N_1DOP_1 + R_{10} & 0 & 0 & 0 \\ 0 & N_iDOP_i + R_{i0} & 0 & 0 \\ 0 & 0 & \ldots & 0 \\ 0 & 0 & 0 & N_mDOP_m + R_{m0} \end{bmatrix} + \boldsymbol{H}_k\hat{\boldsymbol{x}}_{k/k-1}\hat{\boldsymbol{x}}_{k/k-1}^{\mathrm{T}}\boldsymbol{H}_k^{\mathrm{T}} \tag{15}$$

The formula on the right side of equal sign is marked:

$$\boldsymbol{D}_k=\boldsymbol{H}_k\boldsymbol{P}_{k/k-1}\boldsymbol{H}_k^{\mathrm{T}}+\begin{bmatrix} N_1DOP_1+R_{10} & 0 & 0 & 0 \\ 0 & N_iDOP_i+R_{i0} & 0 & 0 \\ 0 & 0 & \ldots & 0 \\ 0 & 0 & 0 & N_mDOP_m+R_{m0} \end{bmatrix}$$
$$+\boldsymbol{H}_k\hat{\boldsymbol{x}}_{k/k-1}\hat{\boldsymbol{x}}_{k/k-1}^{\mathrm{T}}\boldsymbol{H}_k^{\mathrm{T}} \quad (16)$$

In equation (15), diagonal element of noise variance matrix on both sides of the equation represents the amount of each observed noise variance respectively, using the diagonal elements, determining if each component of measurement Z_k is an outlier, discrimination is on the basis of the following:

$$M_{i,i}(k)\in\left[D_{i,i}(k)-\varepsilon_i, D_{i,i}(k)+\varepsilon_i\right] \qquad i=1,\ 2,\ \cdots,\ m \quad (17)$$

In equation $M_{i,i}(k)$ means the i element on the matrix diagonal $E\left[Z_kZ_k^{\mathrm{T}}\right]$, $D_{i,i}(k)$ means the i element on the diagonal matrix $\boldsymbol{D}_k$, ε_i is the disturbance quantity of calculating error.

If the measurement $Z_i(k)$ is normal value , equation (17) stablishes; Whereas measurement $Z_i(k)$ is wild value, equation (17) doesn't establish.

IV.Correcting algorithm

The activation function $f(r)$ is adopted to adjust the detected outliers measurement, reduce influence of the amount outliers measurement to the precision of state estimation, state estimation equation is updated to:

$$\hat{\boldsymbol{x}}_k=\hat{\boldsymbol{x}}_{k/k-1}+\boldsymbol{K}_k(f(r)Z_k-\boldsymbol{H}_k\hat{\boldsymbol{x}}_{k/k-1}) \quad (18)$$

In the equation activation function $f(r)$ has the following features:

1) When r tends to infinity, $f(r)\to 0$;

2) When $r<\mathrm{L}$ or $r\ge\mathrm{L}$, $f(r)$ is a constant, L is the threshold value;

3) $f(r)$ falls in monotonous and continuously differentiable.

To keep the orthogonality of innovation process of the revised kalman filter, the activation function must be related to the measurement Z_k, so this article use piecewise smooth activation function [20] as shown in the following equation (19).

$$f_i(r_i)=\begin{cases}1 & r_i\le d_i \\ d_i/r_i & r_i>d_i\end{cases} \qquad i=1,\ 2,\ \cdots,\ \mathrm{m} \quad (19)$$

In equation: $r_i=\sqrt{M_{i,i}(k)}$, $d_i=\sqrt{D_{i,i}(k)+\varepsilon_i}$.

The fixed train of thought in equation (19) is when measurement is not wild value, the gain of activation function is 1, maintain the integrity of the innovation; when measurement is outlier, $r_i>d_i$,and activation function < 1, the implementation of outliers restrictions is realized, and according to the dilution of precision of current measurement , realize weighted limit in different precision ranges of the outliers.

V.Test experiment and results

With 0.006 / h laser gyro inertial navigation system and GPS OEM615 boards as inertia/satellite integrated navigation system, the main performance indicators are shown in Table 1 below.

TABLE I
Device performance

laser gyro inertial navigation system	OEM615 GPS OEM615 GPS boards
zero offset：100ug	positional precision：1.2m
gyroscopic drift：0.006°/h	speed precision：0.03m/s
heading precision：0.02°（σ）	
alignment precision：0.005°（σ）	
positional precision：1-2m（σ）	

Track test is on some test sites in Beijing, the process is as follows: track detector static alignment for 5 min, then according to the planned route, measuring distance is 300 m. Reference datum choose track geometry state detector GRP1000 Ann berg, its precision indicators are shown in Table 2 below.

TABLE II
Performance of GRP1000

items	accuracy
total station Leica TCRP 1201+R400	angle measurement accuracy 1 s, range accuracy 1+1.5ppm
alignment/high-low	0.5mm

Orthogonal fault-tolerant to outliers and remain of outliers were used respectively to carry out inertial/satellite signals combination, can be seen from figure 1, under the condition of more GPS signal outliers, method of the combined navigation location result is smoother, using the method of orthogonal fault-tolerant to outliers, while integrated navigation location results with ordinary outliers result in a large number of phase steps.

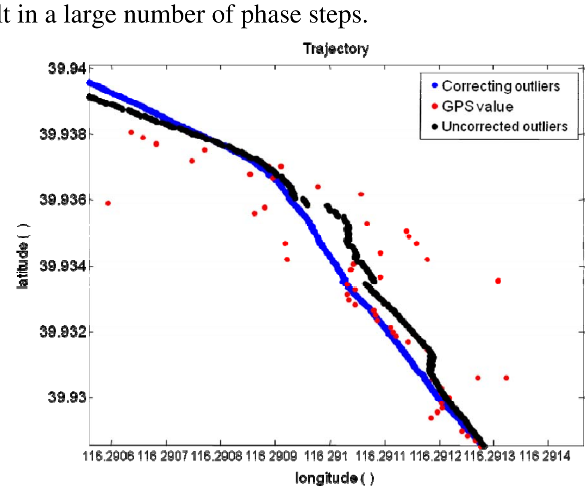

Fig. 1 Integrated navigation location information and the location of the GPS.

Using the above two kinds of integrated navigation results to solve orbit parameters, and the measured data of track geometry detector GRP1000 as a benchmark, calculate the accuracy of results of high-low unsmoothness parameters (Fig.2) and rail irregularity parameters (Fig.3) of short wave 30m string high. It is obvious that orbit parameters calculated by orthogonal outliers method are smooth and precisions are high, results with ordinary outliers result in a large number of phase steps, parameters are not continuous and precisions are low. Calculated two different processing methods of calculating accuracy are shown in figure 3 below, the calculating precision of alignment parameter is increased from 2.65 mm to 0.37 mm, calculating precision of high and low parameter is increased from 1.94 mm to 0.58 mm, thus verify the correctness and validity of the application of orthogonal fault-tolerant to outliers method in inertia detection system of track geometry status.

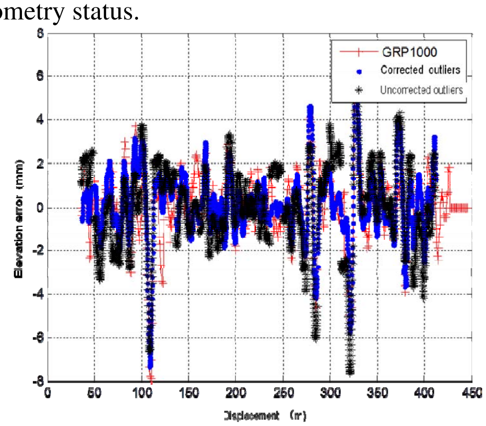

Fig. 2 Height result.

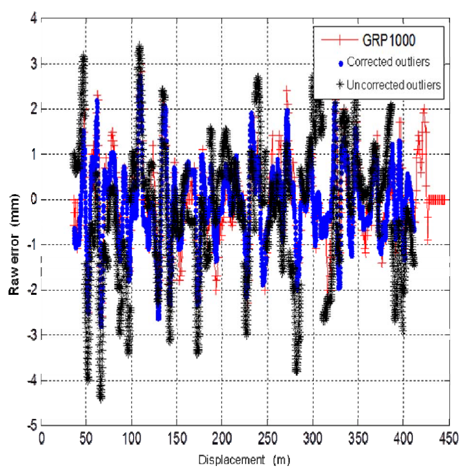

Fig. 3 Raw result

TABLE III
PERFORMANCE OF GRP1000

items	pure inertial precision(σ)	precision adjustment of dynamic attitude	datum
alignment 30m string	2.65mm	0.37mm	GRP1000 Geometry status detector of absolute orbit
high-low 30m string	1.94mm	0.58mm	GRP1000 Geometry status detector of absolute orbit

VI. CONCLUSION

In the actual process, the outliers in observation appear frequently. Under using general Kalman filtering, the outliers in observation may lead to inaccurate state estimation, reduction of filtering precision, even filtering divergence, and so on.The proposed method uses principle of innovation orthogonality, combined with the satellite signal DOP value, identifies and limits the outliers measurement, reduces the effect of outliers track precision in Kalman filtering, while ensuring stability and accuracy of the filtering . Test results verify the effectiveness of the proposed method, within a distance of 300m, by fault-tolerant to outliers method can improve the measuring accuracy of inertia detection system of track geometry status to one order of magnitude, the method has better practical value in engineering application.

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