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Research on Improving the Accuracy of Speed and Distance Measurement of Train by Redundant Convolution Fault-tolerant Analysis and Multiple Data Fusion

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Abstract: In the current operation and control system of trains on the rail transit system, the accuracy of speed and distance measurement is not high and there is a large difference between the measured result and actual situation, because it is generally determined by the fixed adhesive force configured in the system, especially in the condition of idling in low-speed situations and the slipping when braking in high-speed situations. In this study, the redundant convolution fault-tolerant analysis was proposed for self-inspection of speed to identify whether the speed and distance measuring equipment is working normally and the safety redundancy structure of the coding odometer and radar was proposed to guarantee the reliability of speed and distance measurement. In this way, the accuracy of speed and distance measurement was improved and the safety of the train and the comfortableness of passengers was ensured. The proposed method was verified in the simulation environment.

Key words: Accuracy of speed and distance measurement, redundant convolution fault-tolerant analysis, multiple data fusion

INTRODUCTION

Many cities in China have constructed the Communication Based Train Control System (CBTC), including Beijing, Shanghai, Nanjing, Kunming, Wuhan, Shenzhen, Guangzhou and Wuxi. The position of mobile authorization terminal of CBTC trains is determined through processing the message of speeds and positions of the train in the front and the train at the back. The report of train's position is directly related to the actual operational safety of trains. Furthermore, improving the accuracy of report on the position of on-board train can also reduce the arrangement of passive beacons and thus reduce the construction cost of the signal system. Meanwhile, the improvement of accuracy on the train's position can effectively reduce the head and tail envelope and improve the operation ability. In addition, the train running speed monitored by the speed measuring system is also directly related to ATO (Automatic Train Operation), which affects the comfortableness of passengers. So, how to improve the accuracy of position and speed of train is a vital part in the study of train operation control system.

During the actual operation, the operation section of train is physically confirmed by detecting the axle counter or track circuit and other trackside equipments. The accurate positioning of a train depends largely on the on-board train position report. However, there is an error between the on-board position report and the actual position of the train. In the current system, the actual position of the train is corrected by the location beacon when the train is passing it. But the idling in low-speed situations and the slipping when braking in high-speed situations are generally determined by the adhesive force. The accuracy of this method is not high and there is a large difference between the fixed configuration in the system and the actual situation (Yoshimoto *et al*., 2001; Wang *et al*., 2010; Ciccarelli *et al*., 2012).

To accurately control the train operation, the mathematical model of train shall be determined through the accurate speed feedback and the input vehicle traction information during the experimental stage; and the speed and position report of the train shall be accurately feedback to the on-board controller and regional controller during the actual operation. At present, the position of a train can be confirmed by the integration of speed or the feedback value of multiturn encoder. The speed of a train can be measured by coding odometer, including two methods: Frequency method and periodic method. A pulse will be generated whenever the optical encoder of a coding odometer turns a scale and each pulse is corresponding to a distance. For example, each pulse in an 8-bit coding odometer is corresponding to:

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$$S = \frac{2^*\pi^*r}{2^8}$$

where, r is the wheel radius. The periodic method calculates the current actual speed by the equation v = s/t after measuring the time interval t between two adjacent pulses. The frequency method measures the number of impulses m in a fixed period T, v = n*sec T^{-1}. With the development of semiconductor technology, the frequency of a chip is increasing continuously and the problem that the chip may not be able to accurately measure the pulse period in high speed is no longer existed; in view of the possible error caused by the periodic method in low speed, the current speed measuring algorithm generally adopts the frequency method. The FPGA integrated with DSO is selected as the hardware on the speed and distance measuring board. The FPGA interface is flexible and the DSP is suitable for the fast signal processing (Richard *et al*., 2006; Zhang *et al*., 2011; Nakache, 1984).

At present, generally two coding odometers are used in a system to measure the speed. But when one odometer is failed or idling, the accuracy will be greatly reduced. If installing a radar device on the train body, the problem of idling or slipping will no longer matter anymore. And then, these data are processed and judged in real time through self-correlation and different correlation to find out if the speed and distance measuring equipment is working normally. Combined with the fusion of multiple data, the accuracy of speed measurement and positioning will be greatly improved (Verhille *et al*., 2004; Pintea *et al*., 2011; Djeziri *et al*., 2009).

PRINCIPLES AND METHODS

When the subway is running, the on-board ATO/ATP system needs the feedback speed of the train to adjust the input of the traction system and braking system in real time to achieve the expected speed. Therefore, the speed measurement of on-board equipment becomes a key point in the ATO/ATP system. In the current project, a coding odometer (OPG) is generally installed on the diagonal brake axle of the train. Its principle is measuring the actual rotational speed of the train through the linkage rotation of the optical encoder and the axle. The actual running speed of the train wheel can be obtained by multiplying the rotational speed by the wheel radius. The actual speed of the train is one half of the sum of speeds of the former wheel and the latter wheel. In this study, an on-board radar is installed for the speed measuring system, which achieves the redundancy of speed measurement and increases the reliability. The on-board radar uses the Doppler principle and measures the actual running speed of the train through the reflection of wave. The radar is installed on the train and it can directly measure the actual displacement changes of the train and has nothing to do with the traction system. So the installation of a radar can reduce the requirement of human intervention when the driving wheel or OPG is malfunctioning. Figure 1 shows the flow diagram of speed and distance measurement algorithm (Zhu *et al*., 2010; Barrero *et al*., 2008).

In comparison, the output of optical encoder is accurate when the speed is low and its resolution ratio varies from 8-12-bit. But radar and other means are required due to the potential idling situation. If two of the three feedback speeds from OPG1, OPG2 and radar are zero, then the train is in idling situation. Otherwise, the obtained data can be input into the Kalman filter to measure the speed. When turning or in high speed, the train may have the problem of slipping. But the actual train displacement measured by the radar is accurate, so the speed can be revised by combining the radar and OPG. The Kalman filter can anticipate which will effectively eliminate the impact of sampling time and basically solve the current determination of speed. The actual running distance of the train is the integration of speed but various factors in the real environment will generate error. Therefore, the transponder installed on the line can assist the train positioning. A message information will be received after the train passed through the ground transponder and the time receiving the message will be recorded. And then, the beacon code will be unpacked and read and the position of the passed beacon can be confirmed by comparing with the existing

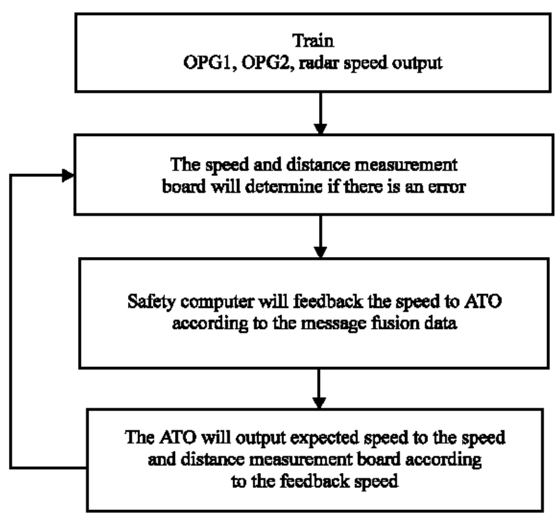

Fig. 1: Flow diagram of speed and distance measurement algorithm

line information. The position of the train can be revised by comparing the mileage of the beacon and the position information at the moment of receiving the message (Chuang *et al*., 2008).

When the train is running, the measured speed may change suddenly due to the idling and slipping problem. In the current conditions, we need to identify the error and put an end to the impact of speed error alarm and delay in normal driving conditions. The speed and distance measurement proposed in this paper uses the safety redundant configuration of the coding odometer and radar to guarantee the safety of speed and the reliability of the speed and distance measuring board. The treatment method can be divided into two parts: Monitoring detection (fault diagnosis) and fusion of multiple data (estimation). The monitoring detection realizes the self-checking of the speed through the redundant convolution fault-tolerant analysis. The multiple data fusion achieves the purposes of denoising and anticipation by using the Kalman filter (Djeziri *et al*., 2009).

REDUNDANT CONVOLUTION FAULT-TOLERANT ANALYSIS METHOD AND TEST RESULTS

The method of redundant convolution fault-tolerant analysis is used in this study for the monitoring detection. The expected speed of ATO and the speed of OPG are convolution differently correlated through DSP. The expected speed of ATO is identified as the input and the speed of OPG as output for fast Fourier transform (FFT):

$$e_r(j) = \sum_{k=1}^{N} E_r(k).e^{-\frac{2.\pi.i}{N}.(j-1).(k-1)}$$
$$j = 1, ..., N$$

$$s_r(j) = \sum_{k=1}^{N} S_r(k).e^{-\frac{2.\pi.i}{N}.(j-1).(k-1)}$$
$$j = 1, ..., N$$

The convolution of input and output is calculated:

$$C_{es}(j) = e_r(j).s_r^*(j)$$

FFT is done:

$$C_{ES}(k) = \frac{1}{N}.\sum_{j=1}^{N} c_{es}(j).e^{-\frac{2.\pi.i}{N}.(j-1).(k-1)}$$
$$k = 1, ..., N$$

The error indicator is set as:

$$R = \frac{1}{N}\sum_{j=1}^{N} C_{ES}(k)$$

Through comparing R and our threshold value, we can tell if this speed has error. The operation of the above convolution is realized on DSP. The use of DSP can greatly reduce the calculation time:

$$\begin{cases} \text{if } R \leq Th \text{ bool} = 0 \\ \text{if } R > Th \text{ bool} = 1 \end{cases}$$

where, the threshold value Th shall be regulated and measured according to the actual situation. Bool = 0 means abnormal speed, bool = 1 means normal speed.

We denote this value as bool_OPG1_cross. To increase the robustness and prevent mistaking the true value as the error value, the input speed signal is processed by self-correlation convolution and its value is denoted as bool_OPG1_self. All values are shown in Table 1 when the OPG1, or OPG2, or radar or two of them are used.

Under the normal state, cross = 1, self = 1; Under the delayed state, cross = 0, self = 1; (caused by traction delay but the actual running is normal and the output is not changing in time with the input).

Sudden changes of input cause the sudden changes of output, cross = 1, self = 0, (speed inflection point, during acceleration and deceleration, output changes with input).

Abnormal state, cross = 0, self = 0; (idling or unknown abnormal of OPG).

DATA FUSION METHOD AND TEST RESULTS

The core idea of Kalman filter is revising by using the difference between the input value and judged value. The system is receiving two groups of data from OPG and radar in real time, so the variance of output value, OPG

Table 1: Self and cross correlation convolution

bool_OPG1_cross	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
bool_OPG1_self	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
bool_OPG2_cross	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
bool_OPG2_self	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0

Red represents that both the values of OPG1 and OPG2 can be used; blue represents that the value of OPG2 is used and green represents that the value of OPG1 is used (OPG1 = OPG2); black represents that only the radar value can be used and the train wheels are in severely abnormal state and radar can be maintained to the minimum after multiple iterations. The basic concept of this algorithm is T_{n-1} anticipating a value, comparing the T_{n-1} anticipated value and the T_n value and then revising the weight coefficient.

The speed of the next period is predicated by using the new weight. The speed at time T_n judged at time T_{n+1} is mainly affected by the number of iterations and noise (Larsen *et al*., 1999).

During the modeling process, we need to discretize our model at first and write down the equation of state at the same time:

$$\begin{cases} x_k + 1 = A.x_k + B.u_k \\ y_k = C.x_k \end{cases}$$

where, the objectivity of the system is matrix $O = [C, CA,.., CA^{n-1}]^T$ which is full rank. But in the actual system due to the existence of interference noise, we shall change the model into:

$$\begin{cases} x_{k+1} = f\ (x_k,\ u_k) + \alpha_k \\ y_k = g(x_k) + \beta_k \end{cases}$$

where, K is the parameter in Luneburg observer. The structure of observer and anticipation device is:

$$\begin{cases} \hat{x}_{k|k} = \hat{x}_{k|k-1} + K.\ (y_k - C.\hat{x}_{k|k-1}) \\ \hat{x}_{k+1|k}\quad A.\hat{x}_{k|k} + B.u_k \end{cases}$$

Then the difference between the judged value and the actual value is:

$$\begin{aligned} \hat{x}_{k|k} &= \hat{x}_{k|k} - x_k \\ &= \hat{x}_{k|k-1} + K\ (y_k - C\hat{x}_{k|k-1}) - x_k \\ &= \hat{x}_{k|k-1} + K\ (Cx_k + v_k - C\hat{x}_{k|k-1}) - x_k \\ &= \hat{x}_{k|k-1} - x_k + K\ (-C(\hat{x}_{k|k-1} - x_k) + \beta_k \\ &= (I - KC)\,\hat{x}_{k|k-1} + K\beta_k \end{aligned}$$

$$\begin{aligned} \hat{x}_{k|k-1} &= \hat{x}_{k+1|k} - \hat{x}_{k+1} \\ &= A\hat{x}_{k|k} - Ax_k - \alpha_k \\ &= A\hat{x}_{k|k} - \alpha_k \end{aligned}$$

By introducing the generated error into the iteration to revise the transfer function:

$$\hat{x}_{k|k} = (I - KC)\,\hat{x}_{k|k-1} + K\beta_k$$

$$P_{k|k} = (I - KC).P_{k|k-1}.(I - KC)^T + K.R.K^T$$

$$P_{k+1|k} = A.P_{k|k}.A^T + Q$$

Q represents the diagonal matrix of the input value within the controllable scope; P represents the variance between the actual value and the measured value. Our purpose is to minimize the variance (Babuskaand and Verbruggen, 1996).

Due to the nonlinear nature of our system, the nonlinear form of Kalman filter shall be used. By assuming:

$$y = T(x) \begin{bmatrix} T_1\ (x_1, \ldots, x_n) \\ \ldots \\ T_P\ (x_1, \ldots, x_n) \end{bmatrix}$$

T represents the nonlinear transfer function. Selecting: $X = m_x + \Delta X$.

And then write it down into the first order form of Taylor's series:

$$y = T(m_x) + \left[\frac{\partial T}{\partial x}\right]_{mx} .\Delta x$$

Programming in MATLAB initialization

```
C=[1/2 1/2]; %% taking the average value between OPG1 and OPG2
xk(1,:)=[0;0]; %% initial velocity 0
R=[0.1];
P=[1 0;0 1];   %% initial equation
K=P*C'*inv(C*P*C'+R);   %% proportional weight
Q=[0.0001];
X=ones(n,1);   %% speed log storage speed
```

Circulation speed measurement; filter automatically revises according to the given R and Q

```
for i=2:n,
y(i)=v.signals.values(i)+random('Normal',0,0.05,1,1);
xk(i,:)=xk(i,:)+K'*(y(i)-C*xk(i,:)'); %% radar filtering
xk(i,:)=xk(i,:)+K'*(x1(i)*0.5+x2(i)*0.5-C*xk(i,:)'); %% OPG filtering
P=(eye(2)-K*C)*P*(eye(2)-K*C)'+K*R*K';
A(i)=(xk(i,1)-xk(i-1,1))*20*0.5+(xk(i,2)-xk(i-1,2))*0.5*20; %% obtaining the acceleration
xk(i+1,:)=xk(i,:)*eye(2)+[0.05*A(i) 0.05*A(i)];
X(i)=(xk(i+1,1)+xk(i+1,2))/2;
P=C*P*C'+Q;
K=P*C'*inv(C*P*C'+R);
end;
```

The design of Kalman filter automatically allocates the optimal weights. Combining with the noise treatment on our FPGA board and after smoothing our input, the anticipated output optimization can be obtained.

Figure 2-7 show the experimental evidence. The unit of x-ordinate is second. The unit of y-ordinate from

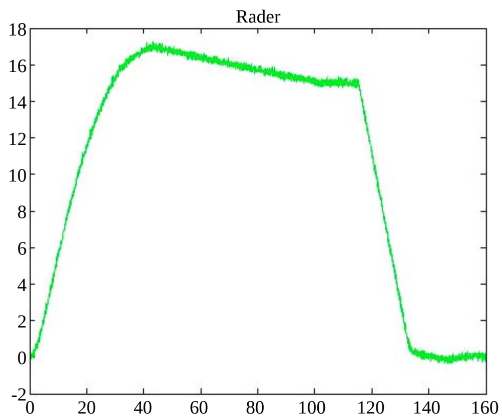

Fig. 2: Actual speed

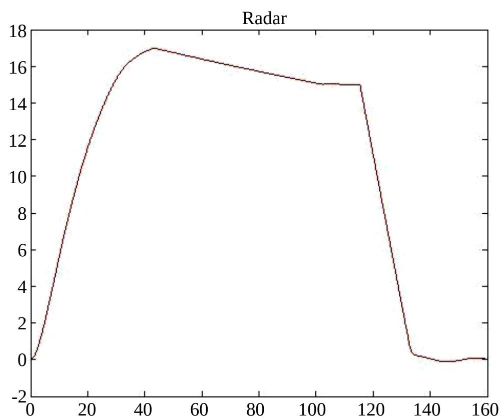

Fig. 3: Radar speed

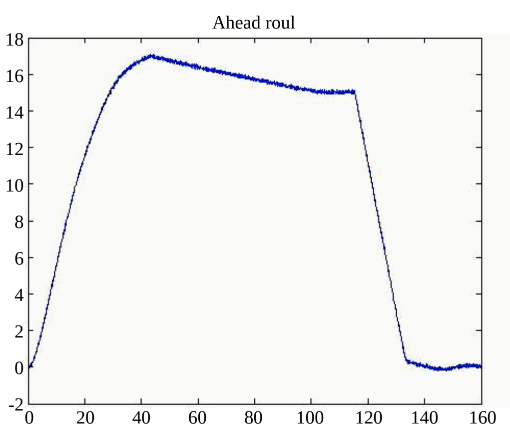

Fig. 4: OPG1

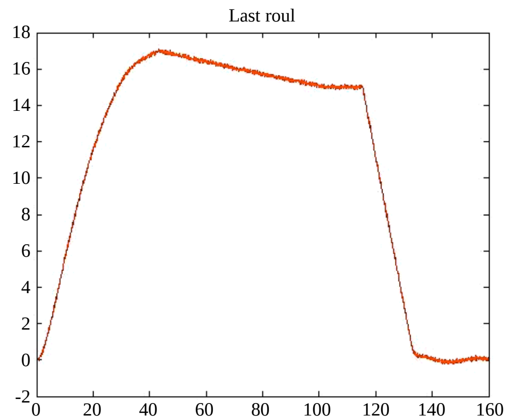

Fig. 5: OPG2

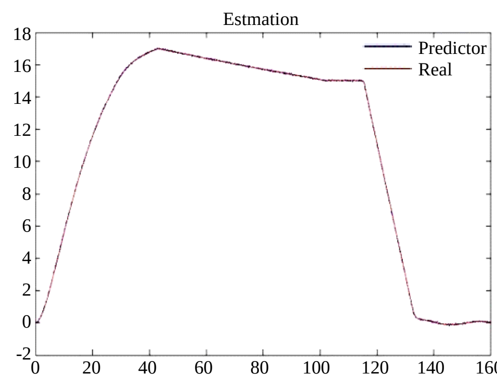

Fig. 6: Judged speed (blue) and actual speed (red)

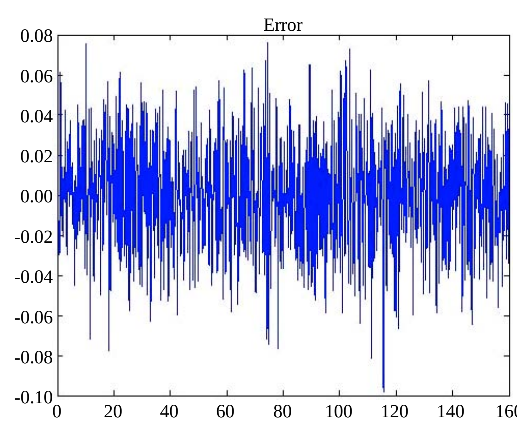

Fig. 7: Difference between judged speed and actual speed (actual speed minus judged speed)

Fig. 2-6 is m sec^{-1}. Figure 2 illustrates the actual operational speed of the train. Figure 3-5 illustrates the input speed by odometer and radar measuring. The judged speed and actual speed are almost same as shown in the Fig. 6. At the same time, from Fig. 7 we could find the tolerance between the judged speed and actual speed is controlled.

CONCLUSION

The safety redundancy structure of coding odometer is used to guarantee the safety of speed and the reliability of the speed and distance measuring board. The redundant convolution fault-tolerant analysis is used for the self-inspection of the speed and to determine the possible problems of traction feedback. The Kalman filter is used for multiple data fusion. While effective denoising, the purpose of anticipation is achieved and the impact to the system by the delay in hardware is reduced. With the practical application and the accumulation and analysis of data, the anticipation analysis system can help the system to accurately pinpoint the location or the module of error and solve and handle the problem from the aspect of software. In future design, the Beidou system will be included in this set of speed and distance measuring system, thus the accuracy of train position report can be further improved. Meanwhile, reasonable combination can be used to reduce the hardware cost of on-board speed and distance measuring system.

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