Position and Speed Measuring Method of Maglev Train Based on Federal Kalman Filter and Information Fusion

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Abstract. The position and speed measuring system is an important part of the High-speed maglev operation control system. The speed and position information accuracy and reliability directly affect the train operation safety. Aiming at the shortcomings and defects of the existing position and speed measuring methods, based on the Federated Kalman filter principle, a multi-source information fusion algorithm is designed to effectively integrate speed and position information from Inertial Navigation System, global satellite navigation system and Doppler radar sensor into the train position and speed measurement. On this basis, a combined position and speed measuring method for maglev train is proposed, it not only has high measurement accuracy, but also has strong robustness and autonomous operation ability. The effectiveness and reliability of the proposed method are experimentally verified based on the MATLAB software simulation platform. The experimental results show that the proposed method can be applied to the real-time position and speed measuring of high-speed maglev.

1. Introduction

With the rapid development of China’s transportation industry, the railway transportation industry, represented by High-speed and Heavy-haul Trains, has become a pillar industry in China, and is a comprehensive embodiment of China’s march towards the world’s modern science and technology power. Among them, maglev train, as an advanced form of rail transit, is one of the future development directions of High-speed railways in China and even the world. In daily railway operation, the accuracy and reliability of real-time location and speed information provided by the train position and speed measuring system not only guarantee the normal operation of the train, but also directly affect the core principle of "Train Safety", which is particularly important in transportation. Therefore, how to develop accurate and reliable new position and speed measuring system to adapt to the rapid innovation of modern railway industry and how to lay a good foundation for the widespread popularization of maglev train in the future has become a primary research direction of many domestic and foreign researchers in the industry.

Different from the ordinary wheel-rail contact train, maglev train realizes the non-contact guidance between train and track through the electromagnetic force. Therefore, it is impossible for maglev train to detect the train speed by installing a tachometer on the axle. In the field of maglev train, Germany and Japan, respectively adopt the absolute position and speed measuring method of inductive coding and the relative position and speed measuring method of cog-slots counting according to their respective technical characteristics and advantages. Current position and speed measuring methods for maglev trains can be divided into relative positioning method and absolute positioning method.
According to the reference of position information [1], as shown in figure 1.

Among them, the method based on maglev initial position and real-time displacement to calculate the train real-time relative position information is called the relative positioning method. This method mainly includes: position and speed measuring method based on inductive line, counting sleepers, long stator teeth-slot signals detection, Doppler radar, and Inertial Navigation System (INS). Ref. [2] on the basis of based on inductive line technology, through the adoption of vehicle antenna to detect alternating magnetic field, under the premise of considering the common-mode interference from the optimized cable model selected the most appropriate magnetic flux density component to achieve reliable speed of maglev train positioning, but the method has high engineering cost and maintenance workload big shortcomings, such as, therefore not suitable for a wide range of promotion. Ref. [3] compared and judged the information of accelerometer, eddy current sensor and radar, and proposed a position and speed measuring method for Medium-low Speed Maglev Train based on counting sleepers. However, its working efficiency is greatly affected by the distance between rail pillows. Ref. [4] based on the long stator teeth-slot signals detection method, put forward a kind of applicable to real-time on-line measurement of discrete time tracking differentiator, and combining with compensation algorithm and switching algorithm, effectively eliminate the error due to the clearance of the stator and the noise, but the fusion algorithm is not wide application scope, long confined to special stator tooth structure. Aiming at the problem that the measurement accuracy of vehicle-mounted Doppler radar is prone to deviation caused by vehicle body vibration, Ref. [5] proposes an automatic correction scheme of double antennas. By integrating the Angle self-correction algorithm, the included Angle and beam width of the track plane can be automatically corrected, and the speed measurement error can be controlled within 1km/h. The disadvantage is that the laser speedometer used in the correction algorithm does not meet the dynamic working mode, so it cannot measure the train speed in real time. Aiming at the inevitable error of radar speed measurement, Ref. [6] proposed a method to correct the inherent deviation of speed measurement. Normalized by radar velocity calculation rate, uniform sampling and panning alignment, speed are obtained, after several rounds of measuring wheel diameter calibration, its effective enhances the speed measuring precision of Doppler radar immunity ability, but the train under complex working conditions in actual operation of the inherent deviation correction method is put forward higher parameters real-time processing requirements. Inertial navigation technology has the advantages of high autonomy, such as not relying on external information and not being disturbed by external environmental factors, so it is widely used in the field of relative position and speed measuring of maglev trains. Ref. [7] proposed a combined navigation scheme combining GNSS with inertial navigation technology, but the application of positioning terminal design is only limited to rail trains. Ref. [8] discusses the application of combined land inertial navigation technology with zero speed correction technology in the military field, and puts forward the future development direction of information fusion.

In addition, the method of obtaining the absolute position of the train based on the known position device beside the rail is called the absolute positioning method. Such methods mainly include: Global Navigation Satellite System (GNSS), query - transponder and pulse width coding. Aiming at the problem that GNSS is susceptible to positioning errors caused by signal blindness, Ref. [9] proposed a data fusion algorithm based on processing GPS signals and gyroscope sensor signals, which greatly reduces the positioning errors of train in the satellite signal blindness. Ref. [10] to line, car running at the same time a variety of complex scenarios for global satellite positioning technology based train running speed curve simulation, for the actual speed positioning system research provides the theoretical support, but the study concluded that the discrete digital trajectory, the larger velocity error against the safety of the railway system of rigid. In addition, the actual performance of the system is limited by the simple motion model and incomplete original parameter information. As to meet the needs of the development of China’s railway industry manufacture, to avoid possible risks, GPS Ref. [11] proposed a with Chinese Beidou navigation satellite system is given priority to, supplemented in combination with the combination of GPS satellite navigation system, but it is still not completely get rid of the dependence on the GPS, and a single speed positioning way, vulnerable to the influence of...
complex topography. Ref. [12] realized the compensation of relative positioning error based on query-transponder and pulse coding technology, and introduced machine learning knowledge to evaluate the sensor state through the method combining software and hardware, which further improved the reliability of the whole system.

Figure 1. Speed and position measurement of maglev train.

The accuracy and reliability of train position and speed measuring are the key performance indexes of the system. The accuracy of train position and speed measuring is closely related to the accuracy of all kinds of sensors used. However, due to the comprehensive consideration of production cost, technology, manufacturing process and many other factors, the solution to improve the accuracy of sensors is not practical. Therefore, in view of the contradiction between the limited detection range of a single sensor, the low measurement accuracy and the high demand for position and speed measuring of High-speed maglev train, the concept of train position and speed measuring information fusion is proposed by the researchers. In view of the limitations of single sensor application, an integrated position and speed measuring system based on multi-sensor information fusion is proposed in Ref. [13] Based on the federated Kalman filter technology. The position information is determined by the distance traveled by the train, and the train speed information is measured by multi-sensor. However, the actual efficiency of the method is limited by various unknown external environment factors, and the complex system composition leads to high cost. In addition, the wheel rail acceleration sensor scheme is not suitable for the position and speed measuring of maglev train. In view of the special requirements of maglev train position and speed measuring, a method of maglev train position and speed measuring is proposed in Ref. [14], which combines relative positioning and absolute positioning technology, realizes cross inductive line, radar sensor and query transponder information fusion by using federal Kalman filter, and overcomes the shortcomings of accumulated error caused by using Doppler radar alone.

It can be seen from the above that the multi-source fusion of the position and speed information of maglev train can not only overcome the performance problems caused by a single position and speed measuring method and a single sensor, but also learn from each other’s strengths to complement each other’s weaknesses, thus greatly improving the accuracy, reliability and anti-interference ability of the position and speed measuring system. Therefore, the integrated navigation based on information fusion is the main direction of the development of train position and speed measuring technology. In view of the disadvantages of current position and speed measuring technology of maglev train, such as high cost, poor autonomy and poor information fusion effect, based on the principle of Kalman filtering, this paper proposes a maglev velocity measurement and positioning system combining absolute positioning and relative positioning. It collects and fuses the three-source position and speed measuring information of INS, GNSS and Doppler radar, and uses the modular design to organically combine the four modules of signal acquisition, communication, storage and processing through Kalman filter fusion algorithm, so as to realize the high-precision position and speed measuring of maglev train. Finally, the simulation model of the system is run on the MATLAB software platform. The experimental results show that through the optimization of the software parameters and the improvement of the system stability, the new combined maglev train position and speed measuring system achieves the expected performance goals, and meets the requirements of driving safety and
reliability on the premise of good accuracy performance.

2. Structure and Principle Analysis of System

In view of the inherent shortcomings of a single position and speed measuring method, the multi-source information fusion position and speed measuring system of maglev train proposed in this paper adopts the structure of multi-module combination. According to the function, the hardware structure of the combined position and speed measuring system can be divided into four modules: speed and positioning, data communication, data storage and information processing, as shown in figure 2. Among them, the position and speed measuring module and data processing module run through the whole system, which is the organic combination of software and hardware. Through the fusion algorithm, the core function module of multi-source data processing.

![Figure 2. The structure composition of position and speed measuring system.](image)

2.1. Structure of Position and Speed Measuring Module

The new combined maglev train position and speed measuring system proposed in this paper integrates the inertial navigation technology Doppler radar technology based on relative positioning principle, global satellite navigation and positioning technology based on absolute positioning principle. It can be seen from figure 2 that the position and speed measuring module for position and speed information acquisition adopts a three-source structure, and realizes reliable autonomous navigation with high accuracy and strong anti-interference ability through the complementary advantages of various methods.

The Inertial Navigation System realizes the position and speed measuring of the train with the object force on the premise of assuming that the object moves at a constant speed [15]. Different from the platform Inertial Navigation System with complex navigation coordinate system and high cost, this paper selects the joint agile inertial navigation technology which does not need stable platform and is suitable for lightweight equipment, which makes the system have the ability of full autonomous navigation independent of external information and not affected by external complex environmental factors. However, INS has the defect that the error of position and speed measuring accumulates with time, so it is necessary to integrate the method with real-time and accurate measurement and control ability to continuously correct the results of position and speed measuring of INS. Global satellite navigation system is the best choice.

The global satellite navigation system mainly consists of three parts: satellite constellation (i.e. normal working satellite network), satellite signal receiver and ground monitoring system. Its speed and positioning performance is not limited to the influence of space-time and azimuth, and has high measurement efficiency and accuracy [16]. In order to overcome the defect of INS accumulation error and avoid the potential dependence risk of GPS, this paper selects Beidou global satellite navigation and positioning system, which is independently developed and built in China. It is not limited to the limitation of time and space, and can provide continuous and accurate real-time speed and position information for Maglev trains all day long to eliminate accumulation error. However, the effectiveness of GNSS is still limited by the special closed terrain along the railway, such as tunnels, and there are uncontrollable factors of satellite signal blind area, so it is necessary to introduce the method of position and speed measuring without working blind area to overcome this deficiency.

In view of the problem of signal blind area in GNSS, this paper integrates Doppler radar
technology in the new type of position and speed measuring system, and adopts the vehicle borne XS-IQ2 radar speed sensor (speed measurement range: 0.1-2000 km/h) to collect the continuous information of maglev train, which successfully overcomes the defect of GNSS work blind area. On the contrary, the Beidou navigation system and the Inertial Navigation System also make a good reference for the vehicle body vibration error correction of the Doppler radar, and realize the complementary advantages of each method.

It can be seen from the structure composition of the above position and speed measuring module and the selection and collocation of each position and speed measuring method in this paper that the combination skill of “Core Advantage” to compensate for “Potential Defects” can improve the comprehensive efficiency of the position and speed measuring system of maglev train as a whole on the one hand, and on the other hand provide the premise for safety redundancy in case of system failure. This provides a good hardware environment for the following software fusion algorithm.

2.2. Function Principle of Information Processing Module

According to the working process, the train combined position and speed measuring system can be roughly divided into two steps: the first step, each sensor in the system will collect its own original information; the second step, with the help of the Federal Kalman filtering algorithm, the original information will be processed efficiently, so as to obtain the train speed and position information detected by each sensor, and finally the information fusion of each sub module can be realized through the fusion algorithm. To sum up, the software system used to realize train position and speed measuring is divided into two main parts: information collection and information processing.

Based on different sources, the original sensor information collected by the speed and positioning module may be mutually exclusive in form. In addition, the above analysis shows that the measurement information obtained by various methods may contain different noise content under different working conditions. Therefore, it is necessary to use MATLAB/Simulink software to process the original speed and position information scientifically through the fusion algorithm. The processing steps are shown in figure 3.

![Figure 3. Software processing step flow of speed and location information.](image)

In order to achieve effective information fusion, this paper proposes a three source information fusion algorithm based on the principle of Federated Kalman filter.

3. The Principle of Fusion Algorithm for Information Processing
In order to effectively process the original information of speed and position collected by the combined maglev train speed and positioning sensor, this paper introduces the Kalman filter principle into the software fusion algorithm.

3.1. A Method of Position and Speed Measuring Based on Kalman Filter
Based on the principle of linear minimum variance estimation and state space method, the method of applying Kalman filter technology to train position and speed measuring can be simply expressed as: the position and speed measuring method of estimating the optimal solution by establishing the state equation and measurement equation of the whole system in the time domain [17-18]. Firstly, the general state equation and measurement program of a single sensor module in the combined position
and speed measuring system are established as shown in equations (1) and (2). (the same for other sensors)

\[ X(k) = \Phi(k,k-1)X(k-1) + \Gamma W(k-1) \quad (1) \]

where \( X(k) \) —— is the state of maglev train at time \( k \). In this paper, location information \( S(k) \) and train speed \( v(k) \) are selected as state variables; \( \Gamma \) —— system noise moving matrix; \( \Phi(k,k-1) \) —— one step transition matrix of state; \( W(k-1) \) —— the system noise at the previous moment of \( k \).

\[ Z_i(k) = H_i X(k) + M_i(k) \quad (2) \]

In the measurement equation, \( Z_i(k) \) —— measurement output of each sensor; \( H_i \) —— measurement matrix of each sensor; \( M_i \) —— measuring noise.

In order to express the information of three sources of sensor conveniently, let \( i = (n,b,r) \). Among them, \( n \) corresponds to Inertial Navigation System, \( b \) corresponds to Beidou global satellite navigation system, and \( r \) corresponds to vehicle Doppler radar system. Select the position information \( S(k) \) and train speed \( v(k) \) as the measurement output; \( R(k) \) is the measurement noise covariance; \( Q(k) \) is the system noise covariance (make the following reasonable assumptions: \( R(k) \) is a positive definite matrix; \( Q(k) \) is a non negative definite matrix). In an ideal case, the system noise and the measurement noise are regarded as the Gaussian white noise whose mean value is zero.

The recursive algorithm of Kalman filter can be obtained as follows:

(1) The Time Renewal Equation is:

\[ X(k,k-1) = \Phi(k,k-1)X(k-1) \quad (3) \]

\[ P(k,k-1) = \Phi(k,k-1)P(k-1)\Phi^T(k,k-1) + \Gamma Q(k-1)\Gamma^T \quad (4) \]

(2) The Renewal Equation of Measurement is:

\[ X(k) = X(k,k-1) + K(k)\left( Z(k) - H X(k,k-1) \right) \quad (5) \]

\[ K(k) = P(k,k-1)H^T(HP(k,k-1)H^T + X(k,k-1))^{-1} \quad (6) \]

\[ P(k) = (I - K(k)H)P(k,k-1) \quad (7) \]

where \( X(k,k-1) \) —— one step prediction value of the train status; \( X(k) \) —— state prediction value of the \( k \)-th train; \( K(k) \) —— Kalman filter gain matrix; \( P(k,k-1) \) —— The error variance matrix of \( X(k,k-1) \); \( P(k-1) \) —— The estimation error variance matrix of the previous time of \( k \); \( P(k) \) —— \( k \)-time estimation error variance matrix; \( H \) —— sensor measurement matrix; \( I \) —— unit matrix; \( Z(k) \) —— sensor measurement at time \( k \).

It can be seen from Eq. (3) - (7) that, given the initial value \( X(0) \) of the state and the initial value \( P(0) \) of the error, the optimal state estimation \( X(k) \) of the maglev train position and speed measuring system at \( k \) time can be calculated according to the measured value \( Z(k) \) of each sensor at \( k \) time.
3.2. Three Sources Fusion Algorithm of Combined Position and Speed Measuring System

In order to integrate the information of Inertial Navigation System, Beidou global satellite navigation system and Doppler radar, the position and speed measuring system of maglev train proposed in this paper adopts the federated Kalman filter technology to achieve the efficient integration of the above three sources of information. The Federated Kalman filter consists of a main filter and several sub filters, The GNSS, ins and Doppler radar sensors in the position and speed measuring system are respectively filtered by the conventional Kalman filter according to the steps of formula (3) - (7). Through the independent time and measurement update of the system state values by each sub filter, multiple groups of local estimation values $X_i$ and covariance matrix $P_i$ of train motion state with different but small difference are obtained; then, the main filter in figure 4 will effectively integrate the local estimation values output by the three sub filters, and finally, the global estimation values $X_g$ and covariance matrix $P_g$ of train motion state are used as the speed and positioning system. The optimal output of the system.

$$X_g(k) = P_g(k) \sum_{i=1}^{b_r} P_i^{-1}(k) X_i(k) \quad (8)$$

$$P_g(k) = \left[ \sum_{i=1}^{b_r} P_i^{-1}(k) \right]^{-1} \quad (9)$$

Among them, $X_g(k)$ —— global estimation of train motion state at time k; $P_g(k)$ —— the estimation error variance matrix of $X_g(k)$.

![Figure 4. Three-source information fusion algorithm block diagram.](image)

3.3. Algorithm Parameter Improvement and Reliability Optimization

Interactively, the main filter will feed back the global estimates to each sub filter one by one according to the optimization principle of weight distribution, which is used to guide the data optimization of each sub filter. The allocation rules are as follows:

$$X_i(k) = X_g(k) \quad (10)$$

$$P_i^{-1}(k) = P_g^{-1}(k) \beta_i \quad (11)$$
where set $\beta_i$ as the distribution coefficient, $i = (n,b,r)$.

In order to achieve the optimal information fusion, the distribution principle of information distribution coefficient is adjusted as follows:

$$
\beta_n = \begin{cases} 
0.6 & (v \leq 50 \text{ km} / \text{h}) \\
0.5 & (50 \text{ km} / \text{h} < v \leq 150 \text{ km} / \text{h}) \\
0.4 & (150 \text{ km} / \text{h} < v)
\end{cases}
$$

(13)

$$
\beta_b = \begin{cases} 
0.3 & (v \leq 50 \text{ km} / \text{h}) \\
0.4 & (50 \text{ km} / \text{h} < v)
\end{cases}
$$

(14)

$$
\beta_r = 1 - \beta_b - \beta_n
$$

(15)

Among them, $\beta_n$ corresponds to Inertial Navigation System, $\beta_b$ corresponds to Beidou GNSS, and $\beta_r$ corresponds to vehicle Doppler radar system.

Analysis of the above distribution coefficient adjustment in time speed segment: in low speed segment, due to the relatively low position and speed measuring accuracy of Beidou global navigation system and Doppler radar sensor, the distribution coefficient is smaller, and the Inertial Navigation System has good performance in low speed segment, which can make up for the shortage of this speed segment, so the distribution coefficient is larger. In the middle and high speed section, the influence of the error in the Beidou position and speed measuring mode on the accuracy will be reduced, and the distribution coefficient can be increased at this time. In addition, when the train is running at high speed, Doppler radar can give full play to its advantages of position and speed measuring, so the distribution coefficient of radar should also be increased at this time.

In the above parameter optimization method, the speed measurement accuracy of each sensor in the position and speed measuring system in different operating speed segments is fully considered. The detailed discussion close to the actual complex situation further improves the reliability and algorithm accuracy of the position and speed measuring system.

In addition, the combined position and speed measuring system proposed in this paper has the potential advantage of safety redundancy. In view of the sudden failure of a sensor in the process of train operation, the software system can not only distribute the distribution coefficient of the failure module to other sub modules of the same level, so as to ensure the stability and fault tolerance of the system in the case of failure, but also make a temporary and reliable prediction of the system state with the help of the prediction and estimation method provided by Kalman filter. That is to say, according to the observation data and state estimation values of the system at the previous time and the current time, the system state in a certain period of time in the future can be reasonably predicted and estimated, so as to realize the safe transition:

$$
X_{k,j} = \Phi_{k,j} E(X_j / Z_1, Z_2, ..., Z_j) = \Phi_{k,j} X_j
$$

(16)

$$
P_{k,j} = \Phi_{k,j} P_j \Phi_{k,j}^T + \sum_{i=j-1}^{k} \Phi_{k,j} \Gamma_{i,j-1} Q_{i,j-1} \Gamma_{i,j-1}^T \Phi_{k,j}^T
$$

(17)

The meaning of each parameter in the formula is as follows: $X_j$——estimated train status at time $j$; $P_j$——the variance matrix of state estimation error at time $j$; $X_{k,j}$——estimated value of train
state at k time (next time) calculated from J time \((k > j, j \text{ represents current time})\); \(\Phi_{k,j}\) —— train state transition matrix from time j to time k;

The state prediction value obtained by Kalman filter can make the system run smoothly when the train does not stop in the middle. On the premise of ensuring the safety of train operation, the comprehensive operation efficiency of the line is improved.

4. Modeling of Maglev Train Motion

After the completion of the software fusion algorithm design, in order to test the performance of the combined position and speed measuring system, it is necessary to build a motion model close to the actual motion state of the maglev train and suitable for theoretical analysis. It is reasonable to assume that the maglev train can be regarded as an inertial body in the state of uniform speed or uniform acceleration, but the acceleration can not be changed in the case of variable acceleration, so the acceleration of the train is kept constant at a certain instant. In addition, the uniform motion model can be equivalent to the uniform acceleration model with zero mean acceleration. Therefore, the uniform acceleration model is chosen to describe the motion state of maglev train. The mathematical model is derived as follows:

\[
S(k) = \begin{bmatrix}
1 & T & \frac{T^2}{2}
\end{bmatrix} S(k-1)
\]

\[
v(k) = \begin{bmatrix}
0 & 1 & T
0 & 0 & 1
\end{bmatrix} v(k-1) + \begin{bmatrix}
1 & 0 & 0
0 & 1 & 0
0 & 0 & 1
\end{bmatrix} \omega_s(k-1)
\]

Among them, \(S(k), a(k)\) and \(v(k)\) represent the displacement, acceleration and speed information of the train at time k respectively; \(\omega_s(k), \omega_a(k)\) and \(\omega_v(k)\) represent the system noise contained in the train displacement, acceleration and speed information at time k respectively.

Set up:

\[
X(k) = \begin{bmatrix}
S(k) \\
v(k) \\
a(k)
\end{bmatrix}, \quad \Phi = \begin{bmatrix}
1 & T & \frac{T^2}{2} \\
0 & 1 & T \\
0 & 0 & 1
\end{bmatrix}
\]

\[
\Gamma = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}, \quad W(k) = \begin{bmatrix}
\omega_s(k) \\
\omega_a(k) \\
\omega_v(k)
\end{bmatrix}
\]

The train discrete state equation and sensor measurement equation corresponding to equations (1) and (2) are as follows:

\[
Z(k) = \begin{bmatrix}
Z_s(k) \\
Z_a(k) \\
Z_v(k)
\end{bmatrix}
\]

\[
H = \begin{bmatrix}
0 & 1 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]
After the above formula is brought into the preset parameter value, the discrete state equation and sensor measurement equation of the train under the condition of uniform acceleration operation can be obtained.

5. Experimental Simulation Analysis
In order to achieve the following performance objectives of the new combined maglev train position and speed measuring system, and finally verify the effectiveness of the three source fusion algorithm.

(1) The refresh rate of speed and positioning data shall be no less than 50 Hz;
(2) The positioning error accuracy is higher than 10 m;
(3) The speed measurement error is less than 1 km/h.

This paper uses MATLAB software platform to simulate the algorithm. In addition, in order to better fit the actual situation, add the system noise standard deviation of simulation, see table 1 for specific parameters.

| Noise category                          | Parameter value |
|-----------------------------------------|-----------------|
| Parametric acceleration noise           | 0.1 m/s²        |
| Velocity noise                          | 0.1 m/s         |
| Position noise                          | 0.5 m           |
| Measurement noise of INS                | 0.5 m/s         |
| Doppler radar measurement noise         | 0.5 m/s         |
| Measurement noise of Beidou navigation system | 0.05 m/s²     |

According to the established acceleration motion model of maglev train, the simulation time is set as 500 s, and the fusion period of main filter is 1 s. through simulation, real-time operation data of train can be generated. Figure 5 is the speed curve simulation of train under uniform acceleration condition. Among them, the blue line represents the original set waveform, and the red line represents the fusion output waveform of the combined speed and positioning system (in figures 5 and 6, the coordinate unit is: Velocity/km/h; Time: s.).

![Figure 5. Simulation results of system speed curve.](image)

![Figure 6. Partial enlarged view of speed curve.](image)

As can be seen from the above figure, the original waveform and the fusion waveform have achieved a high degree of fitting. To facilitate error observation, the speed curve has been partially...
enlarged as shown in figure 6.
Similarly, the position curve and local amplification simulation of the train under uniform
acceleration condition can be obtained as shown in figures 7 and 8 respectively. (The coordinate unit is:
Position: m; Time: s.)

![Figure 7](image1.jpg)  
**Figure 7.** Simulation results of system position curve.

![Figure 8](image2.jpg)  
**Figure 8.** Partial enlarged drawing of position curve.

From the above simulation results, it can be seen that the new combined position and speed measuring method of Maglev Train based on federal Kalman filter and state prediction principle proposed in this paper has reached a high level of accuracy. In the case of adding a number of external interference noise, the system can still maintain a high correction accuracy and stable waveform output, which shows that the position and speed measuring scheme not only has a better measurement accuracy, but also has a strong robustness and autonomous operation ability.

6. Conclusion
In view of the shortcomings of single sensor efficiency in the existing maglev train position and speed measuring system and the poor integration effect in the composite navigation system. Based on the analysis of various methods and sensor error characteristics, this paper proposes a three source combined maglev train online position and speed measuring scheme based on the principle of Federated Kalman filter, which improves and complements the existing maglev train position and speed measuring technology. The specific work is as follows:

(1) By analyzing the advantages and disadvantages of INS, GNSS and Doppler velocity radar sensor, an efficient and reliable hardware scheme is scientifically combined;

(2) Based on the principle of Federated Kalman filter, a three source fusion algorithm is designed to process the original information efficiently. At the same time, the accuracy and robustness of the system are improved by means of optimization of distribution coefficient, safety redundancy and state prediction;

(3) Based on the theoretical analysis, the accurate mathematical model of maglev train under the condition of uniform acceleration is built;

(4) Finally, based on the MATLAB software simulation platform, the validity and reliability of the proposed method are verified by experiments. The results show that the proposed method can be well applied to the real-time position and speed measuring of maglev train.

References
[1] Zhang S C 2008 Research review on position and speed measuring methods applicable to maglev trains *Railway Standard Design* 62 (10) 186-191.

[2] Dai C, Dou F, Song X, et al. 2012 Analysis and design of a speed and position system for maglev vehicles *Sensors* 12 (12) 8526-8543.
[3] Huang S 2018 A combined position and speed measuring method of medium-low speed maglev train based on rail pillow Urban Rail Transit Research 21 (11) 85-87.

[4] Xue S, Long Z, He N and Chang W 2012 A high precision position sensor design and its signal processing algorithm for a maglev train Sensors 12 (5) 42-48.

[5] Li M, Cao L and Wang D 2016 Research on radar sensor algorithm for locomotive speed measurement Sensors and Microsystems 35 (12) 69-71.

[6] Yuan L, Zhao W, Li C, et al. 2013 Error correction method for train speed measurement using Doppler Radar in Train Control System.

[7] Li J and Gao J 2019 Modern tram positioning terminal setup based on Beidou satellite and inertial sensor combined navigation technology Railway Computer Applications 28 (10) pp 60-62.

[8] Wang H 2019 Overview of the development of inertial navigation system technology for land use Optics and Optoelectronic Technology 17 (06) 77-85.

[9] Wang D, Chen G and Yang T 2017 Research on a fast and high-precision GPS combined positioning method Journal of Railway Science 39 (02) 67-73.

[10] Zhou H 2015 Research on Train Group Satellite Positioning Trajectory Simulation System.

[11] Su R and Liu X 2011 Application of Beidou satellite navigation system in railway industry Railway Communication Signal Engineering Technology 8 (06) 28-30.

[12] Zhang D, Long Z, Xue S, et al. 2012 Optimal design of the absolute positioning sensor for a high-speed maglev train and research on its fault diagnosis Sensors 12 (8) 10621-10638.

[13] Yu W 2012 Research of Multi-Sensor Integration System for train speed and position measurement Applied Mechanics and Materials 1473 (212) 1920-1925.

[14] Li X, Liu X and Shi L 2013 Research on information fusion in maglev train speed measurement and location Journal of University of Electronic Science and Technology of China 42 (01) 87-91.

[15] Zhao W 2019 A brief analysis on the application and development of inertial navigation technology China Equipment Engineering 10 (20) 153-154.

[16] Fan R, Zhao W, Han Z and Li W 2016 Application review of GPS surveying technology in engineering surveying and mapping Western Resources 42 (02) 46-47.

[17] Wang L 2019 Simulation of underwater fusion localization algorithm based on Kalman filter Electroacoustic Technology 43 (07) 17-19.

[18] Tan P, Wu Z and Kang Y 2019 Research on combined navigation algorithm to suppress Kalman filter emanation Geospatial Information 17 (09) 109-112+11.