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# A system for measuring straightness of chute running in fully mechanized shearer

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***Abstract:*** *Intelligent and unmanned" is the main trend of the development of modern coal mining in my country. The fully mechanized shearer is the main equipment for large-scale coal mining. The measurement before advancing, the straightness of the chute is calculated through the measurement, and the position reference is provided for the subsequent advancing of the chute. At present, the chute straightness measurement equipment for fully mechanized shearers in China mainly relies on imports, and localization is in its infancy. The National Energy Coal Mine Mining Machinery Equipment R&D Center has tested and verified that the product chute straightness measurement accuracy has reached the same level as that of foreign imported products. At present, the research and development system is in the operation test of the underground fully mechanized shearer in Huangling Coal Mine.*

***Keywords:*** *Fully mechanized shearer, Chute straightness, Inertial Combination System*

## 1. Introduction

Coal mining device is a modern mine excavation system. During coal mining, its long arm is cut back and forth on the chute. If the chute is bent too much, the movement of the long arm working face on it will damage the chute, cause coal machine failure, and affect mining. The coal progress has brought great economic losses. Therefore, in order to ensure the safe operation of coal mining equipment, the position curve of the chute is obtained by measuring the movement trajectory of the long arm working face, that is, the straightness information of the chute is transmitted to the hydraulic control system, and the control system controls the straightness information based on the information. The hydraulic system pushes the chute at a precise distance to ensure that the track straightness of the long arm working face meets the index requirements in the next movement.

## 2. Design

Inertial navigation technology is that it is passive. It only needs to provide the latitude and longitude information of the initial position once, and can continuously provide information such as attitude, heading, position and speed of the carrier relative to the geographic coordinate system. The shortcoming of error accumulation can be compensated by regular calibration with its own internal algorithm in combination with ranging equipment.

Research the combination, mechanism and control technology of inertial measurement unit + odometer suitable for coal mine fully mechanized mining equipment, establish inertial navigation solution and error compensation model , design self-compensation for accumulated errors, integrate information collected by inertial navigation and vision, and create inertial navigation The combined system, by collecting the position and attitude of the coal machine working face and the rocker arm , solves the problems of measuring the straightness of the chute of the fully mechanized mining equipment and determining the attitude of the rocker arm of the coal machine , and realizes the automation and intelligent remote control of the fully mechanized mining equipment operation process. Among them, the measurement of the straightness of the chute is the main content of the engineering application research at the current stage.

The core idea is to give full play to the high-precision and high-sensitivity characteristics of inertial devices to provide real-time attitude changes and heading changes for the shearer; use the odometer to measure the mileage increment of the shearer relative to the starting point, and build a navigation system with the inertial system. The position calculation system plays a role in suppressing inertial errors; in

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order to obtain the precise position coordinates of the shearer in the independent mining engineering coordinate system, it is transmitted to the comprehensive processing system through the data link, and the inertial and odometer information fusion is used for the fully mechanized mining. The control system provides location information, and the system framework is shown in Figure 1.

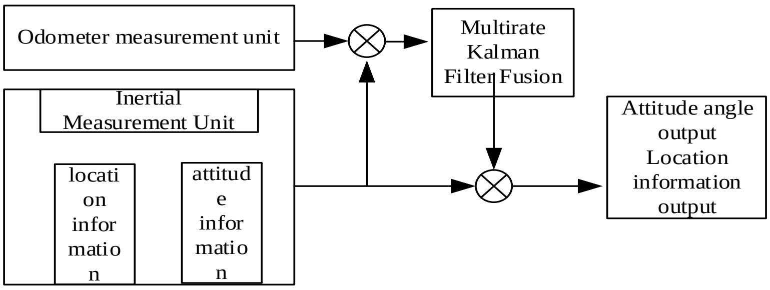


*Figure 1: Combined inertial/odometer measurement system.*

## 3. Technical principle and hardware circuit diagram

Set the forward position of the shearer, the cantilever cutting axis and the vertical axis of the fully mechanized shearer as the axes of the coordinate system , and use the gyroscope and accelerometer to calculate the roll angle, the pitch angle of the device and the heading of the device during the operation of the device At the same time, the information fed back by the odometer is used to adjust the error, solve the trajectory of the fully mechanized mining device, and form the operation model of the coal mining device [1].

Due to the passage of time, the inertial navigation error will become larger and larger [2]. The coordinate system of the northeast sky is adopted. It can be concluded that the spatial coordinate system of the fully mechanized mining device is positioned as in the $S_{\mathrm{n}} = S_b^n S_b$. formula: $S_n$is the displacement increment vector of the $S_b$device at the $n$point; is the displacement increment of the device shaft encoder at $b$time per unit time; $C_b^n$is $n$the direction cosine matrix of the device at the point $b$ time, is the following formula

$$c_b^n = \begin{bmatrix} \cos\gamma\cos\varphi & sin\theta sin\gamma + cos\theta sin\varphi & cos\theta sin\gamma cos\varphi - sin\theta sin\varphi \\ \cos\gamma\cos\varphi & -sin\theta sin\gamma sin\varphi + cos\theta cos\varphi & -cos\theta sin\gamma cos\varphi - sin\theta sin\varphi \\ -\sin\gamma & sin\theta cos\gamma & cos\theta cos\gamma \end{bmatrix}$$

In the formula: θ, γ, φ are the roll, heading and pitch angles of the shearer attitude measured by the built-in inertial element of the inertial navigation device, respectively. After iterating, the position of the device is obtained, see Eq.

$$P_{nj}(t) = P_{nj}(t-1) + S_n(t)$$

In the formula: $P_{nj}(t)$, $P_{nj}(t-1)$is the coordinate position of the device 's first $j$sampling time $t$and sum $t$ —1; $S_n(t)$is the displacement increment vector of the device in each time period. Because the measurement error of the device is fixed and will not change with the movement, the strapdown inertial navigation method combined with the odometer is designed to calculate the device error and feed it back to the device, so that it can correct the running attitude by itself. In the $y$axis direction, add $\Delta D$it, yes Mileage increment. formula:

$$\begin{bmatrix} \Delta px \\ \Delta py \\ \Delta pz \end{bmatrix}_n = C_b^n \begin{bmatrix} 0 \\ \Delta D \\ 0 \end{bmatrix}_b \begin{bmatrix} \Delta px & \Delta py & \Delta pz \end{bmatrix}_n^T$$

The output mileage increment of the odometer $\begin{bmatrix} 0 & \Delta D & 0 \end{bmatrix}_b^T$in the strapdown inertial navigation coordinate system; it is the mileage increment in the device carrier coordinate system.

The working face automatically finds the straight model, simplifies the coal mining face of the device, and uses the normalized vector group to design. The model is shown in Figure 2:

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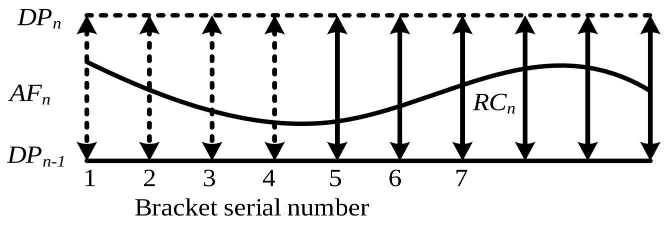


*Figure 2: Mathematical model of curved surface of chute*

The chute straightness measurement and chute advancing process are shown in Figure 3:

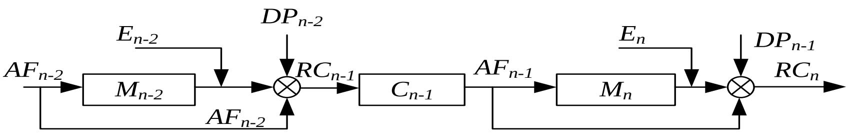


*Figure 3: Flow chart of chute straightness measurement and chute advancement*

$DP_N$is the ideal working surface for the first cutting $n$; $RC_n$it is the $n$straightness corrected for the first $AF_n$ cutting; it is the actual working surface after the first $n$ cutting. $M$ To measure the cut, a curve $E_n$of device flatness was obtained $AF_n$after this cut. The control error $E_n$of the first $n$knife cutting is the source of the error. The compensation formula is

$$RPC_n = DFP_n - AFP_n$$

$C$In order to compensate for cutting, during the cutting process, the main control device sets the exact height value of all hydraulic props, and the system corrects the straightness by itself. Before starting, the master will rely on the curve drawn by the first cut $AF_{n-1}$. Straight line $DP_N$, then the computer calculates the $RC_n$correction value according to the setting algorithm, and pushes the device straight. Because the closed-path algorithm is used to eliminate the accumulated error of inertial navigation [5], the main control system can only calculate after the device cuts a process $AF_n$, and the straightness needs to be completed in two adjacent cuts in order to compensate. The complete process of cutting and transporting coal is the "measure-compensation" operating mode.

Inertial Navigation Coordinate System The $b$system is the upper right coordinate system of the inertial navigation, the navigation coordinate system $n$ The system is the northeast sky coordinate system, the carrier coordinate system $m$ The system is the front right upper coordinate system of the car body. The origin in the system $m$is the center of gravity of the car, the $Y$axis points to the front of the car, the $X$axis points to the right side of the car body, and the $Z$axis points to the roof direction. The $X$axis, the $Y$axis and the $Z$ axis form a right-hand coordinate system. The odometer only has forward speed $V_{odoy}^b$. Formula: $V_{odo}^b = \begin{bmatrix} 0 & V_{0d0y}^b & 0 \end{bmatrix}^T$

The odometer errors mainly include the angle error caused by placement and the scale coefficient error caused by the environmental influence when the device is running to cut the coal seam. Installation errors are ignored for ease of designing the model. The speed of the b system is

$$\tilde{V}_{odo}^b = \begin{bmatrix} 0 \\ (1+\delta k) \\ 0 \end{bmatrix} V_{odo}^b = \begin{bmatrix} 0 \\ (1+\delta k) V_{odo}^b \\ 0 \end{bmatrix}$$

When the IMU is installed in the box, there is an installation angle error between the IMU axis and the box axis when the inertial element is placed. Let the device coordinate system be The transformation matrix of the $C_m^b m$ system and the *b system is*, the speed of the *b system is*

$$\tilde{V}_{odo}^b = C_m^b V_{odo}^m = C_m^b \begin{bmatrix} 0 \\ (1+\delta k) \\ 0 \end{bmatrix} V_{odo}^b = (1+\delta k) \begin{bmatrix} sin\alpha_\varphi cos\alpha_\theta \\ cos\alpha_\varphi \varphi cos\alpha_\theta \\ sin\alpha_\theta \end{bmatrix} V_{odo}^b$$

Where, $\alpha_\theta . \alpha_\varphi$ is the error angle set for the heading and pitch.

Zero-speed correction system selects the SINS system error amount, the odometer scale coefficient, the error angle set by the heading and pitch as the state vector

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$$X = [\varphi_E \quad \varphi_N \quad \varphi_U \quad \delta V_E \ \delta V_N \quad \delta V_U \ \ \delta L \ \ \delta\lambda \ \ \delta h \ \ \varepsilon x \ \varepsilon y \ \varepsilon z \ \nabla x \ \nabla y \ \nabla z \ \delta k \ \delta\varphi \ \delta\theta]^T$$

Among them, it is $\varphi_E \quad \varphi_N \quad \varphi_U$ the attitude error angle of the three directions of the northeast sky, that is, it satisfies:

$$\begin{cases} \dot{\delta}_k = 0 \\ \dot{\delta}_{\alpha_\varphi} = 0 \\ \dot{\delta}_{\alpha_\theta} = 0 \end{cases}$$

Then the system error equation can be expressed as follows:

$$\dot{x}(t) = F(t)X(t) + G(t)W(t)$$

Here F(t) is an 8×18 state transition matrix, G(t) is an 18×6 noise driving matrix, and W(t) is a 6×1 system noise matrix.

Taking the velocity error between the SINS system and the northeast celestial coordinate system as the observation quantity, the system observation equation is expressed as follows:

$$Z_0 = V_{SINS}^n - \hat{V}_{ODO}^n = \begin{bmatrix} V_{IE} - V_{odoE}^n \\ V_{IN} - V_{odoN}^n \\ V_{IU} - V_{odoU}^n \end{bmatrix} = H_0 X + V_0$$

The observation matrix is set to H0, and the observation noise is set to V0.

$$H_0 = \begin{bmatrix} 0_{1\times3} & 1 & 0 & 0 & 0_{1\times12} \\ 0_{1\times3} & 0 & 1 & 0 & 0_{1\times12} \\ 0_{1\times3} & 0 & 0 & 1 & 0_{1\times12} \end{bmatrix}$$

After calculation, it is concluded that using the speed difference of the odometer to constrain the strapdown inertial navigation will affect the height. In order to solve the problem of divergence, the The VnodoU constraint is set to 0, and an equation is established to compensate the height error.

$$Z_v = V_{SINS}^n - V_{ODO}^n = \begin{bmatrix} V_{IE} - V_{odoE}^n \\ V_{IN} - V_{odoN}^n \\ V_{IU} - 0 \end{bmatrix} = H_v X + V_v$$

$$Z_P = [P_{SINS}^u - 0] = [\delta h - 0] = H_p X + V_p$$

$$H_v = \begin{bmatrix} 0_{1\times3} & 1 & 0 & 0 & 0_{1\times12} \\ 0_{1\times3} & 0 & 1 & 0 & 0_{1\times12} \\ 0_{1\times3} & 0 & 0 & 1 & 0_{1\times12} \end{bmatrix} H_p = [0_{1\times8} \ \ 1 \ \ 0_{1\times9}]$$

Inertial navigation parameter error formula

$$\begin{cases} V_n = \tilde{V}_n - \delta V_n \\ P = \tilde{P} - \delta P \end{cases}$$

Among them, $\delta V_n$ is the error value after Kalman filtering, and P is the spatial position of the positioning device after self-compensation. where $\tilde{V}_n$ Vn is the 3D space velocity of the SINS after self - compensation error, the velocity in the inertial coordinate system calculated by the SINS subsystem, $\tilde{P}$ is the position, and $\delta P$ is the spatial coordinate error after Kalman filtering.

## 4. Combination System Simulation

The inertial measurement device constructed by laser gyroscope and quartz plus strapdown velocimeter is used in flexible, laser, optical fiber and MEMS products; Resolution photo odometer. According to the typical working face length and propulsion speed, the simulation calculation is made. It is tentatively determined that the gyro index of 0.005 degrees/hour, the accelerometer index of 1×10-5, and the odometer index of 0.03% are used to substitute the information of these three key components into the navigation error. Model simulation can achieve the technical indicators that the measurement

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accuracy in the 300m working plane is less than 5 cm. The typical simulation calculation results based on IMU + odometer are shown in Figure 4:

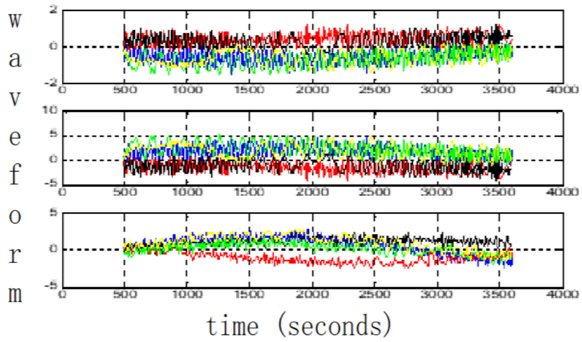


*Figure 4: Simulation results of inertial combined positioning and attitude measurement system*

## 5. Fixed Orbit Experiments

The test site is selected at Zhangjiakou National Energy Coal Mine Mining Machinery Equipment Experimental Center. The fully mechanized mining equipment has a track length of 80 meters, and is equipped with advanced fully mechanized shearers, intelligent control center, hydraulic support equipment, and perfect accuracy testing conditions.

*Figure 5: Inertial navigation installation test*

(1) Lead out the CAN bus on the coal machine, connect it with the CAN bus on the inertial navigation, and transmit the distance moved by the coal machine through the CAN port. The accuracy of the coal machine moving output distance is 1cm. (2) Fix the inertial navigation to the top of the coal machine fuselage, and fix the prism of the total station on the inertial navigation. (3) Set the total station on the side of the starting position of the track, and set one direction as the reference direction. The total station measures the linear offset of the prism relative to the reference direction as the reference value for accuracy comparison. (4) Measure the distance that the points on the track deviate from the reference line at intervals of about 1m, and simultaneously record the data of the total station and the data of the inertial navigation. (5) Inertial navigation measurement accuracy repeatability test. One is to test the repeatability of inertial navigation measurement accuracy at each speed, and the other is to compare the repeatability of inertial navigation measurement accuracy at different speeds. According to the analysis results of the test data, the following conclusions can be drawn:

(1) The measurement accuracy of the inertial navigation system provided can meet the accuracy requirements of fully mechanized coal mining equipment; (2) The measurement error interval of the inertial navigation system is [-5.27cm, +5.06cm], which basically meets the measurement accuracy requirements of fully mechanized coal mining equipment; (3) The repeatability of the measurement accuracy of the provided inertial navigation system itself is millimeter level.

## 6. Unfixed track test

In order to verify the measurement accuracy of the non-fixed track, a vehicle-mounted experiment was carried out on the ground to reconfirm the inertial navigation measurement accuracy. The test site was carried out on the square of Xi'an Coal Machinery Plant (Fig.6). The test vehicle was a modified van. The inertial navigation system was installed in the trunk of the vehicle, and the encoder was installed on the left rear wheel of the vehicle (Fig. 7).

*Figure 6: Experimental site*

*Figure 7: Inertial Navigation System Installation*

(1) Calibration encoder (2) The positioning accuracy measurement drives the car back to the origin, and in accordance with the method of moving forward for a period of time, stopping and moving forward for a period of time, the travel distance varies from 140 meters to 170 meters. When the car stops, use the total station to measure the position of the car, and compare it with the measured value of the inertial navigation. The difference between the two is the measurement error (including the inertial navigation error, measurement method error).

It can be seen from the error results that the test results in the morning are all within the range of 5cm, and the measurement errors in the afternoon are all too large. Especially the 2nd and 3rd trips are obviously out of tolerance. After analysis, it is found that the error is mainly caused by the ranging error of the encoder. The ranging error of the encoder is caused by the rapid turning of the car while traveling. The more the car is turned to the right, the greater the error. Because the wheels have differentials, when turning to the right, the right wheel advances less and the left wheel advances more. The encoder is installed on the left wheel, which leads to inaccurate displacement of the measured car. This directly leads to an increase in the straightness measurement error. This conclusion can be proved from the change of the steering speed curve of the car.

## 7. Conclusion

In view of the characteristics of strong vibration and slow propulsion of the fully mechanized coal shearer, a strapdown inertial measurement device constructed with a high-precision gyroscope and a quartz accelerometer is selected; a high-resolution photoelectric odometer is also selected. According to the typical working face length and propulsion speed, the simulation calculation is made. With the gyro index of 0.005 degrees/hour, the accelerometer index of 1×10-5, and the odometer index of 0.03%, the information of these three key components is entered into the Kalman filter. After that, the technical index of the measurement accuracy of 5 cm in the 300m working plane can be achieved. The product has been tested on fixed track and non-fixed track, and the accuracy has reached the requirements of centimeter level. Currently, the test application test is carried out in Huangling No. 1 well.

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