The Attitude Measurement of Horizontal Directional Drilling Equipment Based on Quaternion and Extended Kalman Filtering Method

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Abstract. For the attitude measurement of drilling tool in horizontal directional drilling, a new method for attitude measurement system based on quaternion and extended Kalman filter (EKF) is presented. The attitude measurement system consists of three-axis accelerometer and three-axis gyroscope. Based on the data information obtained by the inertial sensor, the attitude angle of the drilling tool can be calculated. To limit the errors of angle measurement, this research combines the errors of the sensors and the measurement noise and uses EKF method to obtain three angles. Three angles consist of pitch angle, roll angle, drilling angle. The proposed method was tested by two experiments. Results showed that this method could limit the error of drilling tool attitude measurement and reduce the impact of environmental noise on the measurement.

1. Introduction
In the field of trenchless technology, horizontal directional drilling technology is an important part of this field. By installing measuring unit in horizontal directional drilling tool, the attitude and direction of underground drilling tool can be collected in real time, which provides a new method for urban underground construction. It is an important part of the steering instrument to collect the attitude information of the drilling tool in real time. The accuracy of the measurement system installed inside the drilling tool directly relates to the acquisition of the attitude of the drilling tool and the direction of travel on the ground.

Luo et al. introduced the use of micro-silicon accelerometer for inclination measurement, combined with temperature characteristics of sensor to compensate [1]. Xu Tao et al. proposed a system design method for trenchless horizontal directional drilling equipment, and simulated analysis of azimuth correction [2], but did not research the filtering algorithm to improve the accuracy of angles. Guo et al. described a wireless directional drilling attitude measurement system and explained its structure and attitude measurement method in the system [3]. Liu et al. proposed the method of multi-sensor fusion for posture calculation, effectively reducing the drift error of the sensor [4]. When the horizontal directional drilling equipment is working, the temperature around the measurement system will rise.
Moreover, the movement of the horizontal directional drilling equipment will generate vibration, which will affect the measurement accuracy of the attitude signal of the drilling tool. In addition, the sensor itself has its own errors due to the manufacturing process, which is also a source of errors that could not be ignored. Improving the attitude measurement accuracy of the horizontal directional drilling tool, which can provide reliable monitoring data for ground workers. The paper will design a method to optimize the attitude measurement accuracy of horizontal directional drilling tools based on the designed measurement system.

2. Hardware and design
In the actual construction process, the horizontal directional drilling tool works as shown in figure 1. In the horizontal directional drilling measurement, the whole measuring system is installed in a narrow space at head of the drill pipe. Therefore, the hardware for the attitude measurement needs to be small in size, light in weight, low in power consumption, high in reliability. MEMS devices have strong integrated, and meet the requirements of horizontal directional drilling attitude measurement in terms of volume, power consumption and weight.

As shown in figure 1, we need to measure the attitude of the drilling tool. The hardware measurement system structure in this paper is as figure 2. The hardware system consists of a three-axis accelerometer, a three-axis gyroscope, and a temperature sensor. The control unit uses chip STM32103x, which can meet the requirements of algorithm operation. The power supply module and the power conversion circuit provide a voltage of 3.3V or 5V, which will provide power for the sensor and the chip. The data information of the measurement system is sent to the computer through the serial port, and in the actual measurement, the staff on the ground can read the attitude data.

3. Theory and Method
3.1. Principles of Drilling Attitude Measurement
In the process of horizontal directional drilling tool measurement, the drilling tool information acquisition depends on the internal inertial sensing unit installed in the drilling tool. The attitude information of the drilling tool mainly includes the drilling angle $\psi$, pitch angle $\theta$ and roll angle $\phi$.

The drilling angle refers to the projection of the drilling tool axis on the horizontal plane and the angle between the geographic coordinate system; the pitch angle is the angle between the drilling tool attitude and the horizontal direction; the roll angle is the angle between the vertical direction of the drill string axis and the initial state.

The attitude measurement of the drilling tool underground can be completed by determining the finite rotation of the drilling tool coordinate system relative to the geographic coordinate system. Initially, the drilling tool coordinate coincides with the geographic coordinate system. When the attitude of the drilling tool changes, it can be regarded as the drilling tool coordinate system making the rotation
The geographic coordinate system is defined as \(OX_1Y_1Z_1\), the initial coordinate system of the drilling tool is defined as \(OX_0Y_0Z_0\). According to the rotation order around the Z axis, Y axis, and X axis, a new drilling tool posture is obtained, and the angle \(\psi\), \(\theta\), \(\phi\) is the posture angle of the drilling tool.

![Figure 3. Conversion of two coordinate systems.](image)

The transformation matrix from geographic coordinate system to drilling tool coordinate system is and attitude matrix [5] is as shown in equation (1).

\[
C^b_n = \begin{bmatrix}
\cos\phi\cos\psi + \sin\phi\sin\psi\sin\theta & -\cos\phi\sin\psi + \sin\phi\cos\psi\sin\theta & -\sin\phi\cos\psi \\
\sin\phi\cos\theta & \cos\phi\cos\psi \sin\theta & \sin\phi\cos\psi \\
\sin\phi\cos\psi - \cos\phi\sin\psi\sin\theta & -\sin\phi\sin\psi - \cos\phi\cos\psi\sin\theta & \cos\phi\cos\psi
\end{bmatrix}
\]

(1)

The coordinate conversion can be expressed by the Euler angle method and the quaternion method, but the Euler angle method will have the problem of universal lock when solving the attitude, so the quaternion method is used here.

The quaternion is used to describe the attitude of the drilling tool. It can be regarded that the b system where the drilling tool is at the next moment is obtained by rotating the quaternion \(Q\) of the n system. The quaternion can be expressed as:

\[
Q = \cos\theta/2 + n\sin\theta/2
\]

Differentiating the time \(t\) in equation (2):

\[
\frac{dQ}{dt} = \frac{1}{2}\alpha^b_{\phi}\otimes Q
\]

(3)

Convert \(\alpha^b_{\phi}\) to angular velocity of drilling tool coordinate system \(\omega^b_{\phi}\):

\[
\frac{dQ}{dt} = \frac{1}{2}(q_0 + q_1i + q_2j + q_3k) \otimes (\omega_1i + \omega_2j + \omega_3k)
\]

(4)

The matrix form is as follows:

\[
\frac{dQ}{dt} = \frac{1}{2}\begin{bmatrix}
0 & -\omega_z & -\omega_y & -\omega_x \\
\omega_z & 0 & -\omega_x & \omega_y \\
\omega_y & \omega_x & 0 & -\omega_z \\
\omega_x & -\omega_y & \omega_z & 0
\end{bmatrix} \begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3
\end{bmatrix}
\]

(5)
\( \mathbf{q}_0 \) is the data obtained by the sensor.

Solve the quaternion differential equation (5) using the Picard solution method, the quaternion at time \( t_1 \) is iterated from the quaternion at time \( t_0 \).

\[
\begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3
\end{bmatrix}_{t_1} = \begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3
\end{bmatrix}_{t_0} + \frac{d\mathbf{Q}}{dt}
\]  
(6)

According to the transformation matrix of the quaternion coordinate system.

\[
C^q_n = \begin{bmatrix}
1 - 2(q_2^2 + q_3^2) & 2(q_3 q_0 - q_2 q_1) & 2(q_2 q_1 + q_0 q_3) \\
2(q_3 q_2 + q_0 q_1) & 1 - 2(q_1^2 + q_3^2) & 2(q_1 q_3 - q_0 q_2) \\
2(q_2 q_3 - q_0 q_1) & 2(q_1 q_2 + q_0 q_3) & 1 - 2(q_1^2 + q_2^2)
\end{bmatrix}
= \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\]  
(7)

The calculation formula of the attitude angle is as follows:

\[
\begin{cases}
\theta = \arcsin(A_{32}) \\
\phi = \arctan(-A_{31} / A_{33}) \\
\psi = \arctan(A_{12} / A_{22})
\end{cases}
\]  
(8)

3.2. Extended Kalman Filtering Method

Extended Kalman filtering (EKF) is an approximate solution based on nonlinear function [7]. The Kalman filtering (KF) method is suitable for systems with a linear model, but the noise is not linear during the measurement of drilling tool attitude. Therefore, we can use EKF to deal with nonlinear factors.

The steps of using the EKF method in drilling tool attitude measurement are as follows.

At the beginning, establish the state equation:

\[
X_k = A_k X_{k-1} + E_k
\]  
(9)

Measurement equation:

\[
Y_k = H_k X_k + v_k
\]  
(10)

\( A_k \) is the state coefficient matrix, \( H_k \) is the state transfer matrix. \( E_k \) is the system noise, \( v_k \) is the observation noise, and both of them obey the Gaussian distribution.

In equation (10), the state vector \( X_k \) is:

\[
X_k = [\omega_b, \dot{\omega}_b, a_b]^T
\]  
(11)

\( X_k \) is an n-dimensional vector at time \( k \) and specifically:

\[
\begin{align*}
\omega_b &= [\omega_{bx}, \omega_{by}, \omega_{bz}]^T \\
\dot{\omega}_b &= [\dot{\omega}_{bx}, \dot{\omega}_{by}, \dot{\omega}_{bz}]^T \\
a_b &= [a_{bx}, a_{by}, a_{bz}]^T
\end{align*}
\]  
(12)

\( Y_k \) is the measurement values at time \( k \) and the six-axis data measured by the sensor.

\[
Y_k = [\omega_{bx}, a_{bx}]^T
\]  
(13)
The steps of EKF algorithm proposed in this paper are as follows.
(1) Initialization: Set the initial value of the system.
(2) State prediction: Input the state vector into the equation of state.

\[ \hat{X}_k = f(X_{k-1}) \]  

(14)

(3) Mean square error prediction:

\[ \hat{P}_k = \Phi_{k-1} P_{k-1} \Phi_{k-1}^T + \Phi_{k-1} Q_{k-1} \Phi_{k-1}^T \]  

(15)

\[ \Phi_k = \frac{\partial f(X_{k-1})}{\partial X_{k-1}} \Big|_{X_{k-1} = \hat{X}_{k-1}} \]  

(16)

And it is a 9×9 state transition matrix in this research.

\[ \Phi_k = \begin{bmatrix} I_{3y3} & O_{3y3} & O_{3y3} \\ O_{3y3} & I_{3y3} & O_{3y3} \\ -C_{w} R_{s-1}^k dt & O_{3y3} & I_{3y3} + C_{w} R_{s-1}^k dt \end{bmatrix} \]  

(17)

\(C_{w} R_{s-1}^k, C_{w} R_{s-1}^k\) are rotation matrices from the previous time to the next time.

(4) EKF gain:

\[ K_k = \hat{P}_k H_k^T \left( H_k \hat{P}_k H_k^T + E \right)^{-1} \]  

(18)

(5) Measurement values:

\[ Y_k = H_k \hat{X}_k + v_k \]  

(19)

(6) Status update:

\[ X_k = \hat{X}_k + K_k (Y_k - H_k \hat{X}_k) \]  

(20)

(7) Mean square error update:

\[ P_k = (I - K_k H_k) \hat{P}_k \]  

(21)

Through the above steps, the output signal of the sensor in the drilling tool system can be filtered and we can obtain the processed data. Then, according to the output information and formula, we can calculate and get the attitude measurement angle of drilling tool.

4. Test and Analysis

In the experimental stage, the hardware system with EKF was tested separately in two ways: static stability and dynamic rotation. The measuring range of the accelerometer is set as ±16g and the measuring range of the gyroscope is set as ±2000 °/s. The data information is transmitted from the single chip microcomputer to the laptop through the serial port. And we can use software to draw the data waveform.

4.1. Static Test and Analysis

Place the measurement system on the three-axis turntable to ensure that the X-Y plane of the inertial sensor is parallel to the turntable. Keep the measurement system still for 1 minute, and continue to complete three experiments, with an interval of 3 minutes between each experiment. After collecting the data, the three sets of data are averaged.
According to the figure 4, in the static test, there is a fluctuation in the original data of the accelerometer in the measurement system. After using filter proposed and calculating, as shown in figure 5, the change range of the attitude angle of the three axial outputs is close to 0°, but there is still a deviation of about 0.03°. In this test, the reason why the attitude angle output is not 0° may be the vibration of the surrounding environment or the error of the sensor itself.

4.2. Dynamic Test and Analysis

Place the measurement system on the three-axis turntable, the initial position is the position during the static test. Then slowly rotate the measuring system. Through the serial bus in the hardware system, we can get the angle change during the whole rotation, and draw three angle curves in MATLAB.

According to the curve in figure 6, when the measurement system rotates, the accelerometer output raw data continues to fluctuate. And in fact, the original data in figure 6 contains a lot of interference signals. After filtering and calculation, as shown in figure 7, the angle change curve is smooth.

In order to evaluate the EKF algorithm mentioned in this article further, the output angles is selected and compared with the actual value.

|   | Pitch (°) | Roll (°) | Yaw (°) |
|---|-----------|----------|---------|
| Actual | Estimated | Actual | Estimated | Actual | Estimated |

Table 1. The actual value of three-axis turntable and estimated value of measurement system
value
0
10
20
40

value
0.05
10.3
19.85
40.2

value
0.1
9.36
20.5
40.43

value
0
10
20
40

value
0.05
10.7
20.3
40.83

Figure 8. The attitude error of calculating

5. Conclusion
This paper first proposes a low-cost system for attitude measurement of horizontal directional drilling tool based on MEMS and then combines the quaternion and EKF to establish the improved model for drilling tool attitude angle measurement. The quaternion method solves the problem of Euler angle universal lock. And the EKF algorithm can optimize the output waveform and filter out the noise signal in the original signal.

Through two test experiments, the results show that integrating the EKF method into the attitude angle measurement of drilling tools can limit noise and improve the accuracy of attitude angle measurement. Moreover, the pitch angle accuracy is ±0.3°, roll angle accuracy is ±0.5° and azimuth angle accuracy is ±0.9°. Combined with the actual horizontal directional construction, the angle accuracy of this paper can meet and exceed the actual engineering requirements.

Acknowledgement
This work was supported by The National Natural Science Foundation of China (Grant No.51105209) and Key University Science Research Project of Jiangsu Province, China (Grant No.15KJA460004).

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