Attitude Measurement System of Patrol Inspection Robot Based on Multi-Sensor Fusion

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Abstract: A strapdown inertial attitude measurement system based on STM32F767 and MEMS sensor ADIS16405 is designed to solve the current real-time attitude measurement and navigation control problems of inspection robots. When the gyroscope or accelerometer and the magnetometer are used alone to calculate the attitude angles, the results are susceptible to the external conditions, and therefore have low precisions. In the paper, a Kalman filter is employed to fuse the data of multiple sensors so as to effectively overcome such difficulties. The experimental results show that the accuracy of the Kalman filter is higher than that of a complementary filter. The angle error of Kalman filter is maintained under 1° and can fulfill engineering requirements.

1. Introduction

With the rapid development of mobile robots, inspection robots in the power industry have emerged to reduce the working loads of operation and maintenance personnel. Figure 1 shows the inspection robot experimental platform designed by Inner Mongolia Mechanical and Electrical Control Key Laboratory. Due to the complicated working environment of inspection robots, they are often necessary to work outdoors. Thus, there are disturbance factors such as road undulations and crosswinds, which influence the pose of the inspection robots greatly. Therefore, the navigation control of the inspection robot needs to acquire the attitude information of the carrier in real time.

Lu Chengqiang[1] et al used Kalman filtering to obtain the current running attitude of the car in real time, but due to the low accuracy of the sensors used and the low frequency of the single-chip microcomputer, the accuracy and real-time performance of the attitude measurement system were limited.Sun Weilan[2] et al proposed to modify the value of the gyroscope according to the adaptive complementary filtering algorithm, and obtain the attitude angle by solving. But compared with Kalman filtering, complementary filtering is not easy to determine the high-pass and low-pass cutoff frequencies.In view of the limitations of the existing methods, a strapdown inertial navigation attitude measurement system based on STM32F767 and MEMS sensor ADIS16405 is designed in this paper. Kalman filter algorithm is used to fuse the data measured by gyroscope, accelerometer and magnetometer to realize the accurate measurement of robot's real-time attitude.

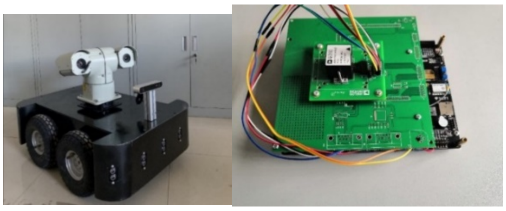

Figure 1. Robot Experimental platform and hardware platform of attitude Measurement system

2. Hardware Design and working principle of attitude Measurement system

This paper builds a hardware experimental platform with STM32F767 as the core controller and ADIS16405 module as the inertial measurement unit. STM32F767 communicates with the PC serial port, sends the data to the host computer through the serial port, and uses MATLAB to process the data to obtain the attitude angle curve. The hardware platform of the inspection robot attitude measurement system is shown in Figure 2.

The working principle is shown in Figure 3: the data process platform acquires the original data of the inertial sensor, and the quaternion number is solved to obtain the initial attitude angle. Through the Kalman filter algorithm, the initial posture value correction and the gyro error compensation are completed, and the corrected attitude angle is obtained. Compared with the complementary filter, it is shown that the attitude measurement after Kalman filter has higher precision.

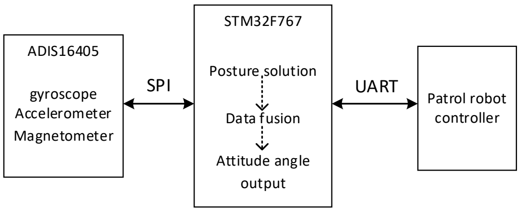

Figure 2. System hardware structure

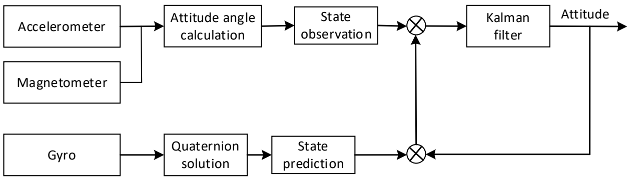

Figure 3. System working principle

3. Attitude angle calculation algorithm

3.1 Definition of coordinate system and attitude description

The motion attitude of the inspection robot is described and represented by the navigation coordinate system and the rotation matrix of the machine body coordinate system. Φ, θ, ψ are the roll angle, pitch angle and heading angle obtained by the x-y-z rotation of the b coordinate system and the n coordinate system. The attitude matrix from the body coordinate system to the navigation coordinate system satisfies the formula (1) [3]. The angle conversion relationship between the geographic coordinate system and the body coordinate system is shown in Figure 4.

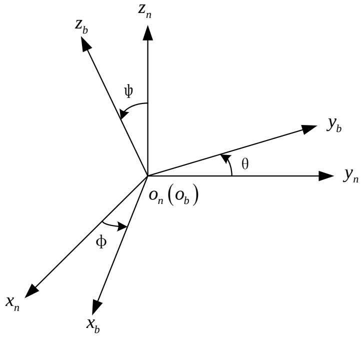

Figure 4.Coordinate system conversion schematic

$$C_b^n=\begin{bmatrix}\cos\theta\cos\psi & \sin\theta\cos\psi\sin\phi-\sin\psi\cos\phi & \sin\theta\cos\psi\cos\phi+\sin\psi\sin\phi\\ \cos\theta\sin\psi & \sin\theta\sin\psi\sin\phi+\cos\psi\cos\phi & \sin\theta\sin\psi\cos\phi-\cos\psi\sin\phi\\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi\end{bmatrix} \tag{1}$$

When converting the data of the carrier coordinate system to the geographic coordinate system, the pose matrix is represented by the quaternion as follows:

$$C_b^n=\begin{bmatrix}q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2)\\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1)\\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2\end{bmatrix} \tag{2}$$

Quaternion vector satisfies differential equation:

$$\dot{Q} = \frac{1}{2} M'(\omega_{nb}^{b}) Q \tag{3}$$

The differential equations of formula (3) can be solved by fourth order Runge-Kutta, and the quaternions can be updated iteratively.

Combining formula (1) with formula (2), the attitude angle is obtained as follows:

$$\begin{cases} \phi = \arctan\left(\dfrac{2\left(q_2 q_3 + q_0 q_1\right)}{q_0^2 - q_1^2 - q_2^2 + q_3^2} \right), \left(-\pi, \pi\right) \\ \theta = -\arcsin\left(2(q_1 q_3 - q_0 q_2)\right), \left(-\pi/2, \pi/2\right) \\ \psi = \arctan\left(\dfrac{2\left(q_1 q_2 + q_0 q_3\right)}{q_0^2 + q_1^2 - q_2^2 - q_3^2} \right), \left(-\pi, \pi\right) \end{cases} \tag{4}$$

Pitch angle and roll angle can be obtained from the information of accelerometer

$$\theta = \arctan\left(-\frac{a_x}{\sqrt{a_y^2 + a_z^2}} \right) \tag{5}$$

$$\phi = \arctan\left(\frac{a_y}{a_z} \right) \tag{6}$$

According to the principle of the magnetometer, the magnetic yaw angle is:

$$\psi = \arctan\left(\frac{m_y^n}{m_x^n} \right) \tag{7}$$

$$\begin{cases} m_y^n = m_z \sin\phi - m_y \cos\phi \\ m_x^n = m_x \cos\theta + m_y \sin\theta \sin\phi + m_z \sin\theta \cos\phi \end{cases} \tag{8}$$

3.2 Complementary filter fusion algorithm

The purpose of the complementary filter algorithm is to synthesize the respective frequency response advantages of the accelerometer, magnetometer and gyroscope, and fuse the three sensor data from the frequency domain to reduce the measurement and estimation errors. It can be seen that processing the noise of multiple sensors from the perspective of the frequency domain is a filtering method with certain advantages. The first-order complementary filtering formula for the attitude measurement system is as follows:

$$angle = k_1 * angle\_acc + (1 - k_1) * (angle + gyro * dt) \tag{9}$$

In the formula, *angle_acc* is the angle value obtained by the accelerometer and the magnetometer, *gyro* is the angular velocity of the gyroscope, *dt* is the sampling time, and k_1 is the weight.

3.3 Kalman filter fusion algorithm

The attitude measurement system of the inspection robot in the power industry uses the Kalman filter algorithm to perform data fusion processing on the attitude angle. The Kalman filter takes the observation of the system as the input of the filter, and uses the estimated value of the system state quantity as the output of the filter, and uses the statistical characteristics of the system noise and the observed noise to make the optimal estimation. The state space description is established for the dynamic model of the inertial sensor. The gyroscope measurement information is used as the process data, the accelerometer and the magnetometer information as the observation data. The equation of state and the observation equation of the system are established as follows [4]:

Equation of state:

$$X_k = AX_{k-1} + BU_k + W_k \tag{10}$$

Observation equation:

$$Z_k = HX_k + V_k \tag{11}$$

In the formula, X_k is the state vector of the system at time *k*, U_k is the input signal of the system at time *k*, Z_k is the measurement vector at time *k*, W_k and V_k are process noise and observed noise, respectively, and *A*, *B*, and *H* are state transition matrices, respectively, input control weight matrix and observation matrix.

The Kalman filter recursive formula can be summarized as the following five formulas:

Pre-estimation of state quantity:

$$\hat{X}_{k|k-1} = A\hat{X}_{k-1} + BU_k \tag{12}$$

In formula (12), $A = \begin{bmatrix} 1 & -dt \\ 0 & 1 \end{bmatrix}$, $B = \begin{bmatrix} dt \\ 0 \end{bmatrix}$, $\hat{X}_k$ is an estimate of the true value X_k of the current state; $\hat{X}_{k|k-1}$ is a pre-estimation based on *k-1* times for *k* times.

Error covariance pre-estimation:

$$P_{k|k-1} = AP_{k-1}A^T + Q \tag{13}$$

In formula (13), P_k is the error covariance matrix of the current state estimate, $P_{k|k-1}$ is the pre-estimated error covariance matrix, and *Q* is the covariance of the system process.

Kalman filter update:

$$K_k = P_{k|k-1}H^T \left[HP_{k|k-1}H^T + R\right]^{-1} \tag{14}$$

In formula (14) , K_k is the modified weighting of the observed deviation $\left(y_k - H\hat{X}_{k|k-1}\right)$, that is, the Kalman gain matrix is the key factor directly affecting the accuracy of the state estimation, and *H* is the gain matrix of the state quantity to the observation measurement, $H = [1 \quad 0]$.

Current state estimate update:

$$\hat{X}_{k|k} = \hat{X}_{k|k-1} + K_k\left(Y_k - H\hat{X}_{k|k-1}\right) \tag{15}$$

In formula (15), y_k is *k* measurements.

Error covariance update:

$$P_{k|k} = \left(I - K_kH\right)P_{k|k-1} \tag{16}$$

The values of *R* and *Q* affect the filtering effect and response speed: the smaller the value of *R*, the faster the response, the faster the convergence; the smaller the value of *Q*, the stronger the ability to suppress noise, but the convergence and response become slower. The initial values of the coefficients of the optimized Kalman filter are set as follows:

$$\hat{X}_0 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} P_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} Q = \begin{bmatrix} 0.03 & 0 \\ 0 & 0.01 \end{bmatrix} \text{R=0.5}$$

4. Results experimental results and analysis

4.1 Angle of rotation analysis

In order to verify the noise reduction effect of the complementary filter method and the Kalman filter method, the power industry inspection robot attitude measurement system is fixed on the three-axis turntable, and the heading angle, roll angle and pitch angle are respectively turned to 35°, and The filtering effects of unfiltered, complementary filter and Kalman filter are compared. The results are shown in Figure 5, 6, and 7, Kalman filtered yaw, roll and pitch angles are 35.46 °, 35.48 °, 35.87 °; complementary filtered yaw, roll and pitch angles are 36.57 °, 36.5 °, 36.86 °; untreated yaw The heading, roll and pitch angles are 39.89 °, 40.57 °, 40.07 °.

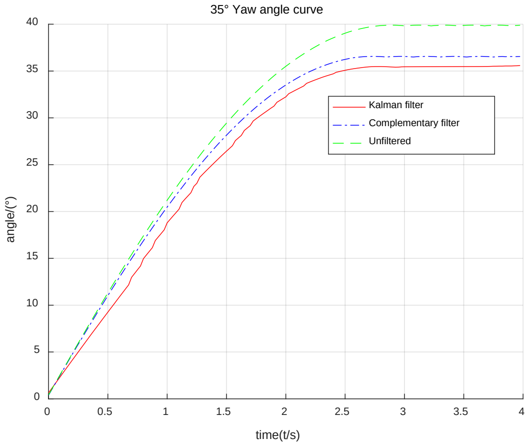

Figure.5. 35°yaw angle curve

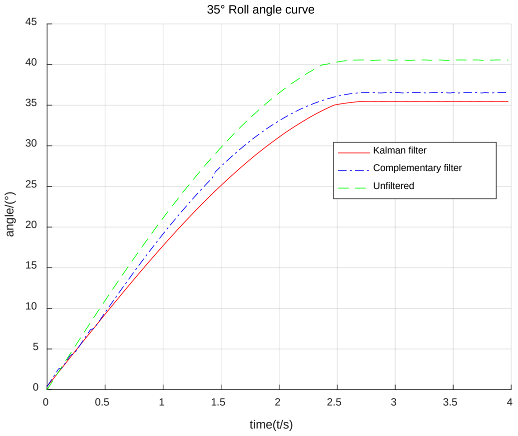

Figure.6. 35°roll angle curve

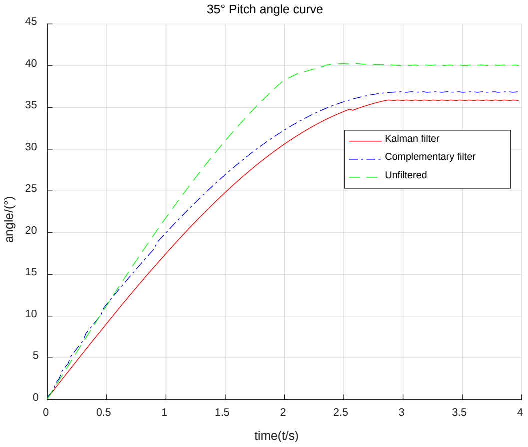

Figure.7. 35°pitch angle curve

4.2 Error analysis of swaying angle

The attitude measurement system makes a ±35° back and forth rocking experiment around the *X*, *Y*, and *Z* axes. Figures 8, 9, and 10 are the angle error curves of the attitude angle of the attitude measurement system. The angle error of the three solutions can be seen from the figure. The Kalman filter's yaw, roll and pitch angle errors are close to 0.5 °,1 °, and 0.5 ° ;the complementary filter's yaw, roll and pitch angle errors are close to 2 °,1.5 °, 1.5 °;angular errors of unfiltered yaw,roll and pitch angles are close to 5 °, 7 °, and 5 °.

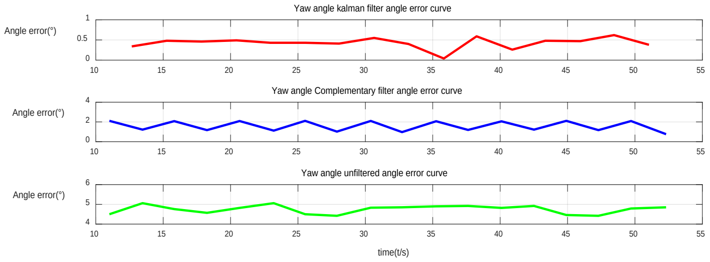

Figure.8. Yaw angle error curve

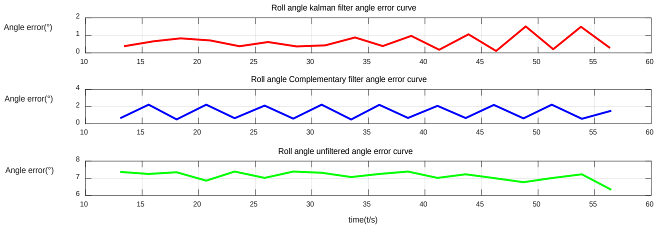

Figure.9. Roll angle error curve

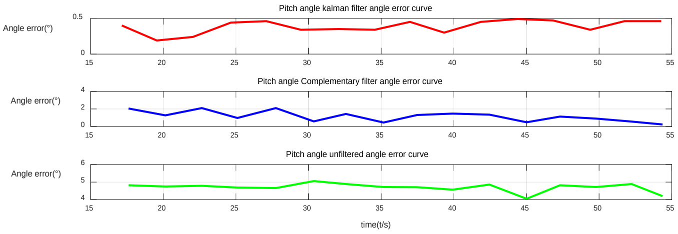

Figure.10. Pitch angle error curve

Table 1, 2, and 3 use statistical knowledge to derive angular errors for the three directional angles. It can be seen from the table that the yaw, roll and pitch of the Kalman filter are 0.38 °, 0.64° and 0.46 °. The average angle errors of the yaw, roll and pitch of the complementary filter are 2.09°, 1.36° and 0.56 °. Unfiltered yaw, roll and pitch angles have average angular errors of 4.79°, 7.13° and 4.89°.

Table.1. angle error of yaw angle

Measure\Filter type	kalman filter	complementary filter	unfiltered
$\lvert\Delta\psi 1\rvert$	0.34	1.22	5.06
$\lvert\Delta\psi 2\rvert$	0.48	2.08	4.76
$\lvert\Delta\psi 3\rvert$	0.46	1.17	4.57
$\lvert\Delta\psi 4\rvert$	0.49	2.09	4.82
$\lvert\Delta\psi 5\rvert$	0.43	1.12	5.06
$\lvert\Delta\psi 6\rvert$	0.43	2.11	4.5
$\lvert\Delta\psi 7\rvert$	0.41	1.02	4.42
$\lvert\Delta\psi 8\rvert$	0.55	2.1	4.83
$\lvert\Delta\psi 9\rvert$	0.4	0.97	4.85
$\lvert\Delta\psi 10\rvert$	0.04	2.07	4.9
$\lvert\Delta\psi 11\rvert$	0.59	1.19	4.92
$\lvert\Delta\psi 12\rvert$	0.26	2.06	4.82
$\lvert\Delta\psi 13\rvert$	0.48	1.22	4.92
$\lvert\Delta\psi 14\rvert$	0.47	2.11	4.46
$\lvert\Delta\psi 15\rvert$	0.62	1.17	4.42
$\lvert\Delta\psi 16\rvert$	0.38	2.09	4.79
average$\lvert\Delta\psi\rvert$	0.43	1.61	4.76

Table.2. Angle error of pitch angle

Measure\Filter type	kalman filter	complementary filter	unfiltered
$\lvert\Delta\theta 1\rvert$	0.4	2.05	4.82
$\lvert\Delta\theta 2\rvert$	0.19	1.27	4.75
$\lvert\Delta\theta 3\rvert$	0.24	2.1	4.79
$\lvert\Delta\theta 4\rvert$	0.44	0.97	4.69
$\lvert\Delta\theta 5\rvert$	0.46	2.1	4.66
$\lvert\Delta\theta 6\rvert$	0.34	0.58	5.06
$\lvert\Delta\theta 7\rvert$	0.35	1.43	4.89
$\lvert\Delta\theta 8\rvert$	0.34	0.45	4.72
$\lvert\Delta\theta 9\rvert$	0.45	1.31	4.71
$\lvert\Delta\theta 10\rvert$	0.3	1.47	4.57
$\lvert\Delta\theta 11\rvert$	0.45	1.35	4.86
$\lvert\Delta\theta 12\rvert$	0.49	0.48	4.05
$\lvert\Delta\theta 13\rvert$	0.47	1.13	4.82
$\lvert\Delta\theta 14\rvert$	0.34	0.9	4.72
$\lvert\Delta\theta 15\rvert$	0.46	0.56	4.89
$\lvert\Delta\theta 16\rvert$	0.46	0.23	4.2
average$\lvert\Delta\theta\rvert$	0.39	1.15	4.7

Table.3. angle error of roll angle

Measure\Filter type	kalman filter	complementary filter	unfiltered
$\lvert\Delta\varphi 1\rvert$	0.38	0.65	7.37
$\lvert\Delta\varphi 2\rvert$	0.66	2.23	7.25
$\lvert\Delta\varphi 3\rvert$	0.83	0.51	7.35
$\lvert\Delta\varphi 4\rvert$	0.71	2.23	6.86
$\lvert\Delta\varphi 5\rvert$	0.38	0.65	7.39
$\lvert\Delta\varphi 6\rvert$	0.62	2.12	7.02
$\lvert\Delta\varphi 7\rvert$	0.37	0.6	7.39
$\lvert\Delta\varphi 8\rvert$	0.43	2.23	7.32
$\lvert\Delta\varphi 9\rvert$	0.88	0.5	7.07
$\lvert\Delta\varphi 10\rvert$	0.39	2.21	7.25
$\lvert\Delta\varphi 11\rvert$	0.97	0.68	7.39
$\lvert\Delta\varphi 12\rvert$	0.18	2.09	7.02
$\lvert\Delta\varphi 13\rvert$	1.06	0.67	7.23
$\lvert\Delta\varphi 14\rvert$	0.11	2.2	7.01
$\lvert\Delta\varphi 15\rvert$	1.51	0.63	6.77
$\lvert\Delta\varphi 16\rvert$	0.21	2.23	7.01
$\lvert\Delta\varphi 17\rvert$	1.49	0.58	7.23
$\lvert\Delta\varphi 18\rvert$	0.28	1.52	6.33
average$\lvert\Delta\varphi\rvert$	0.64	1.36	7.13

It can be seen from the above analysis that the attitude angle error of the Kalman filter is kept within 1°, and it can be seen that the follow-up of the ADIS16405 is good, and the dynamic performance of the ADIS16405 is good, and the dynamic measurement accuracy of the robot attitude measurement system is satisfied.

5. Conclusion

In this paper, Kalman filter algorithm and complementary filtering algorithm are used to fuse the data collected by inertial sensor ADIS16405, and the fusion effect of complementary filtering and

Kalman filtering is compared. The dynamics experiment of turntable verifies that the attitude angle obtained by Kalman filtering is higher. Meet the requirements of the attitude measurement system for real-time performance. Provide accurate angle information for subsequent attitude control system design. In view of the good stability of the Kalman filter algorithm, the designed attitude measurement system has strong engineering application value.

Acknowledgements

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