Design method of measurement errors of MEMS-IMU in attitude capture clothing

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Abstract. Attitude capture clothing is widely used in virtual anchor, virtual fitting and other fields, and MEMS-IMU is the key component to realize high cost-performance attitude capture clothing. However, a precision turntable is needed in order to estimate gyroscope’s static biasing, and measurement errors of MEMS-IMU are difficult to be obtained. Based on the problem, both attitude and gyroscope’s static biasing are estimated in field through a Kalman filter, a design method of measurement errors is proposed for improving attitude’s accuracy. In the proposed method, a mathematical model of measurement errors is given, and the optimal values of measurement errors are obtained by analysing the relationship between attitude’s accuracy and measurement errors. A MEMS-IMU with name of MPU9250 and size of 3 mm*3 mm*1 mm is used for verifying the feasibility of the proposed method. Experimental results show pitch, roll and yaw deviate from the reference values by 0.008°, 0.006° and 0.6° respectively when the MEMS-IMU keeps movement at a constant speed in arbitrary trajectory, which is significant for promoting the application of MEMS-IMU in attitude capture clothing.

1. Introduction

Attitude capture clothing is widely used in virtual anchor, virtual fitting and other fields. A solution of attitude capture clothing is given in Figure 1 including clothing, a control unit, 15 micro-electro-mechanical systems inertial measurement units (MEMS-IMUs) and several conductors. The control unit includes a Bluetooth, a micro-controlled unit and a battery, in which Bluetooth transmit attitude to a remote server. Based on our experience, the proposed solution for attitude capture clothing is much more cost-performance compared with methods by cameras [1]. Unfortunately, MEMS-IMU’s errors including gyroscope’s static biasing and measurement errors would result in user’s attitude presenting larger errors. Many researchers estimate gyroscope’s static biasing by multi-position calibration [2-4], however, the rotation rate of earth is 0.1°/s, which is much less than gyroscope’s noises. Then, a precision turntable is needed in order to calibrate gyroscope’s static biasing. Moreover, measurement errors could be obtained based on the Allan Variance (AV) or the Generalized Method of Wavelets Moments (GMWM) [5]. Caused by complexity and large amount of computation, both the AV and the GMWM are hard to apply to mobile terminal. Usually, the user’s pitch and roll are firstly estimated by using a MEMS-IMU, and then the user’s yaw is estimated by using a magnetometer. However, the measurement results of magnetometer are easily affected by magnetic materials.

In order to avoid using turntable and magnetometer, both the user’s pitch, roll and the gyroscope’s static biasing are estimated by MEMS-IMU, then the user’s yaw is calculated based on gyroscope’s measurement results without static biasing. MEMS-IMU’s measurement errors is crucial for deciding
attitude’s accuracy, however, the existing works directly provide experimental results or empirical values, which result in the design of measurement errors lacking of theoretical and experimental guidance. Based on the problem, a design method of measurement errors is proposed, in which a mathematical model of measurement errors is given, and the optimal values of measurement errors are obtained by analysing the relationship between attitude’s accuracy and measurement errors.

2. Theoretical basis

Figure 2 shows a block diagram of virtual fitting, in which MEMS-IMU is utilized to detect user’s attitude in 3D space. Then, user’s pose could be synchronously displayed in virtual fitting system through the model of 2D-3D alignment. Therefore, attitude’s accuracy is important for keeping user’s pose consistent with avatar, in order to enhance the feasibility of clothes simulation.

Assuming user’s frame on the left of Figure 3 is on navigation frame, and user’s frame on the right of Figure 3 is called body frame, then direction cosine matrix $C^b_n$ from body frame to navigation frame is given for updating avatar’s pose [6]. The update of user’s attitude is divided into 3 steps as...
shown in Figure 4. First, by setting \( C_{b3}^a \) (the third row of \( C_b^a \)) and gyroscope’s static biasing \( b_i \) as a \( 6 \times 1 \) state vector \( X \), then it could be estimated as \( X_i^+ \) by using gyroscope’s output \( y_{G,j} \), in which \( \omega_j \) is angular velocity, \( b_i \) is static biasing equalling \( b_{i-1} \) plus \( n_b \), and \( n_b \) and \( n_G \) are white Gaussian noise. The \( X_i^+ \) is the initial value of \( X \), and the \( P_i^+ \) is the error covariance matrix of \( X_i^+ \). Second, by measuring the gravity acceleration \( g \) based on accelerometer’s output \( y_{A,i} \), the estimated error of \( X_i^+ \) could be calibrated as \( X_i^+ \), in which \( a_{i+1} \) is external acceleration, \( n_a \) is white Gaussian noise, \( H \) is observation matrix and \( M_{i+1} \) is the measurement error of \( g \). Moreover, \( k \) is the impact factor of \( a_{i+1} \) upon the measurement error of \( g \). Finally, user’s attitude including yaw \( \psi \), pitch \( \theta \) and roll \( \phi \) at the moment \( i+1 \) is updated. The \( \psi_i \), \( \theta_i \) and \( \phi_i \) are the initial yaw, pitch and roll respectively. The equations in Figure 4 are explained in detail in reference [7].

![Figure 4. The process of user’s attitude update](image)

In order to obtain accurate user’s attitude at the moment \( i+1 \), the measurement errors of \( n_G^2 \), \( n_a^2 \), \( n_b \), \( k \), \( X_i^+ \) and \( P_i^+ \) should be estimated properly. Based on the importance of measurement errors estimation, a design method of measurement errors is proposed for improving attitude’s accuracy.

3. Design method

Keep MEMS-IMU level and still for a period of time, the outputs of gyroscope and accelerometer are sampled as \( y_{G,1}, y_{G,2}, \cdots, y_{G,n} \) and \( y_{A,1}, y_{A,2}, \cdots, y_{A,n} \), then \( n_G^2 \) and \( n_a^2 \) are calculated as equation (1).
\[
n^2 = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{y_{G,i}}{n} \right)^2, \quad n^2_s = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{y_{A,i}}{n} \right)^2
\]

Assuming the initial values of \( \psi_i, \theta_i, \phi_i \) and \( b_i \) are 0, the initial value of \( X \) would be \( X^* = [0, 0, 1, 0, 0, 0]^T \). Then \( P^* \) could be calculated by using error covariance. When MEMS-IMU is still, \( y_{G,i} \) equals \( b_i + n_{G,i} \). As \( n_{G,i} \) is white Gaussian noise, the mean value of \( y_{G,i} \) is

\[
\sum_{i=1}^{n} \frac{y_{G,i}}{n} = \frac{\sum_{i=1}^{n} b_i + \sum n_{G,i}}{n} \approx \frac{\sum b_i}{n}
\]

Assuming \( n_b \) is constant, \( b_x = b_1 + (n-1)n_x \). Based on the equation (16), \( n_b \) is as equation (3).

\[
n_b = \frac{2 \sum_{i=1}^{n} y_{G,i} - 2 nb_i}{n(n-1)}
\]

Based on the above mathematical model, the values of \( n^2_g, n^2_s, n_b, X^* \) and \( P^* \) could be estimated. Moreover, taking the \( k \) as independent variable and the difference between the proposed attitude and the reference attitude as dependent variable, the optimal \( k \) could be obtained when dependent variable reaches to the minimum value. Thus, all of the measurement errors could be estimated based on the proposed method, and the estimated errors could be corrected by the iterative process of Kalman filter.

4. Experimental results

A MEMS-IMU with a name of MPU9250 and size of 3 mm*3 mm*1 mm is adopt for verifying the proposed method, which includes a 3-axis gyroscope, a 3-axis accelerometer and a 3-axis magnetometer. In this experiment, the MEMS-IMU kept movement slowly at a constant velocity and in arbitrary trajectory. The user’s attitude calculated by the accelerometer and the magnetometer could be regarded as reference attitude, which is used to evaluate the performance of the proposed attitude calculated by the gyroscope and the accelerometer through a Kalman filter.

The sampling frequency and \( g \) are set to 100 Hz and 9.8 m/s\(^2\). The MEMS-IMU is firstly kept level and still for 1 minute, then kept slowly movement at a constant velocity and in arbitrary trajectory for 3 minutes, and finally restore to level and still again for 1 minute. The reference attitude calculated by accelerometer and magnetometer named by \( \theta_{ref}, \phi_{ref} \) and \( \psi_{ref} \), and the proposed attitude is calculated by substituting the estimated measurement errors into Kalman filter.

The measurement errors are estimated by two steps. First, based on the 6000 sampling values of gyroscope and accelerometer during the first minute, \( n^2_g, n^2_s, n_b, X^* \) and \( P^* \) are calculated as 5.8e-6, 0.0013, 0.00017, \([0, 0, 1, 0, 0, 0]^T\) and \( \text{diag} \) \( (2.9e-5, 8.9e-5, 0.17, 2.6e-5, 1.6e-6, 2.3e-6) \) respectively, where \( \text{diag} \) means diagonal matrix. Second, the \( k \) is estimated based on \( n^2_g, n^2_s, n_b, X^* \) and \( P^* \). As the accumulation effect of gyroscope’s noise, we choose the error between the proposed attitude and the reference attitude in the last minute as dependent variable, in which the sampling point is chosen as 28000. And, \( k = 0.1*(j-1) \) is as independent variable, in which \( j \) is changed from 0 to 40.

The simulation results of relationship between attitude errors and \( k \) are shown in Figure 5. The yaw error has the minimum value 0.1° when \( j \) equals 2 and 5, the minimum error of pitch is -9.3e-4° when \( j \) equals 1 while the minimum error of roll is 0.0024° when \( j \) equals 17. As the variation ranges of both pitch and roll are much less than that of yaw, \( j \) is finally set to 5, namely, \( k \) equals 0.4.
By using the estimated measurement errors, the proposed pitch, roll and yaw over the whole 5 minutes are shown in Figure 6, in which the reference pitch, roll and yaw are also presented used to evaluate the proposed attitude. Experimental results show the proposed attitude is highly consistent with the reference attitude. Besides, during the last level and still period, namely, the sampling points are changed from 25000 to 30000, the pitch, roll and yaw deviate from the reference values by 0.008°, 0.006° and 0.6° respectively, which demonstrate the feasibility of the proposed method.

Figure 5. Attitude’s errors versus $j$ when $i=28000$

Figure 6. The proposed and reference attitude

5. Conclusions
A design method of MEMS-IMU’s measurement errors is proposed in this paper, in order to improve the accuracy of user’s attitude. In the proposed method, a mathematical model of measurement error is given, and the optimal values of measurement errors are obtained. Theoretical analysis and experimental results shown in the paper imply the feasibility of the proposed method.

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