Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

# Development of a Low-cost IMU by Using Sensor Fusion for Attitude Angle Estimation

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**Abstract:** The objective of this research was to explore the use of data information of a low-cost IMU to provide an attitude angle with acceptable accuracy for agricultural robot. This work was an attempt to create attitude angle estimation system via sensor fusion method based on a triple gyroscope and a tri-axis accelerometer in this low-cost IMU. The used algorithm processed and integrated the data from the gyroscope and the accelerometer using a mean filter and a Kalman filter. Under this algorithm, the experiment data showed that the estimation precision was improved effectively. It can solve noise jamming, and be especially suitable for the robot which is sensitive to the payload and cost effective.

*Keywords:* Kalman Filter; Mean Filter; Sensor Fusion; Attitude Estimation; IMU Sensor.

## 1. INTRODUCTION

In autonomous navigation field, it is necessary to obtain the attitude and position of agricultural robot. It is the basic of navigation control. Only on this basis, we can continue to carry out the further work, such as path planning or obstacle avoidance. Consequently, a suitable sensor is needed to calculate the attitude of the agricultural robot. An inertial measurement unit (IMU) is such a sensor to measure the attitude in three axes. The IMU, as one kind of navigation sensor, working with global positioning system (GPS), geomagnetic direction sensor (GDS), or machine vision, is widely used in the robot navigation field today.

Normally, an IMU calculates the attitude based on two parts in its body. One is the gyroscope, and the other is the accelerometer. There are no problems to get the attitude angle just by three axis gyroscope, but it depends on the measurement accuracy of the IMU. At the same time, the system error will be accumulated with time. It could not be competent to work long time. In addition, the agricultural robot runs in variable speeds, so the data measured only by accelerometer will mix with strong noise. It is not appropriate for calculating the attitude angle. Using the fiber optic gyroscopes-based IMU can solve the problem, but it is costly for a navigation sensor of an agricultural robot, which is not conducive to the commercialization and popularization of agricultural robot. In order to be economically acceptable to the farmers the application of the robot farming system, a low-cost navigation system is necessary to consider (Noguchi and Barawid, 2011).

The objective of this paper was to explore the use of data information of a low-cost IMU to provide an attitude angle with acceptable accuracy for agricultural robot application. The data processing was to use sensor fusion principle via integrating the data from the gyroscope and the accelerometer in this IMU. It included a mean filter for pre-processing and a Kalman filter for sensor fusion. The experiment performance showed that it can solve noise jamming and provide stable attitude angle estimation.

## 2. MATERIALS AND METHODS

### *2.1 Inertial Measurement Sensor*

A small low-cost IMU (Fig. 1) from Seiko Epson Corporation was used as the inertial sensor on the agricultural robot for this research. This IMU with six degrees of freedom is very compact of 24×24×10 $mm^3$, the weight is 7 grams. Fig. 2 shows the block diagram of this IMU. It is composed of a triaxial quartz micro electro mechanical systems (QMEMS) gyroscope and a triaxial micro electro mechanical systems (MEMS) accelerometer. The outputs of this IMU include chip temperature, triaxial angular rates and linear accelerations. The main performance and electrical specifications shows in Table.1.


Fig. 1 Appearance of the low-cost IMU

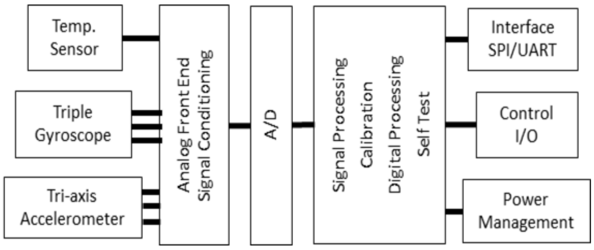



Fig. 2 Block diagram of the IMU

Table 1. Main performance & electrical specifications

| PARAMETERS | TYPE | UNIT |
|---|---|---|
| GYROSCOPE | | |
| Dynamic Range | ±300 | deg/s |
| Initial Error | 0.5 | deg/s |
| In-Run Bias Stability | 6 | deg/hr |
| Angular Random Walk | 0.2 | deg/√hr |
| Noise Density | 0.004 | (deg/s)/√Hz |
| ACCELEROMETER | | |
| Dynamic Range | ±3 | G |
| Initial Error | 8 | mG |
| In-Run Bias Stability | 0.1 | mG |
| Velocity Random Walk | 0.04 | (mG/sec)/ √hr |
| Noise Density | 0.06 | mG/√Hz, rms |

An accelerometer in this low-cost IMU was used for measuring the triaxial linear acceleration. In the nature, as we know, the gravity acceleration vector always directs to the center of the earth. Fig. 3 shows the coordinated frame of this IMU. The measured value of accelerometer is the projection addition of gravity acceleration and absolute acceleration (Chen et al., 1994). So when the IMU keeps static, the relationship between the output value of accelerometer and tilt angle (Roll, Pitch) is not linear, but trigonometric function. Fig. 4 shows attitude angle relation of the accelerometer in coordinate.

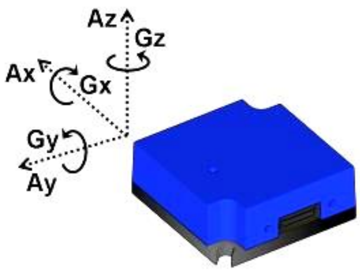



Fig. 3 Coordinated frame of the IMU

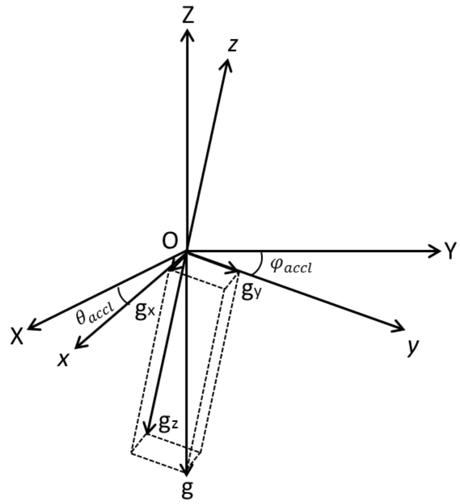



Fig. 4 Attitude angle relation of the accelerometer in coordinate

Coordinate O-XYZ is the geodetic coordinate system. And coordinate o-xyz is the IMU body-fixed coordinate system. The tilt angle between axis OX and axis ox is named pitch. The tilt angle between axis OY and axis oy is named roll. The relationship among the components of gravity acceleration is shown in (1).

$$g = \sqrt{g_x^2 + g_y^2 + g_z^2} \tag{1}$$

where g is the gravity acceleration. $g_x$ , $g_y$ and $g_z$ respectively is gravity acceleration components in axis *ox*, *oy* and *oz*.

Above this, based on trigonometric function, the expressions of the attitude angle can be obtained by (2) and (3).

$$\theta_{accl} = -\arcsin \frac{g_x}{g} \tag{2}$$

$$\varphi_{accl} = 90^\circ - \arccos \frac{g_y}{g \cdot \cos \theta_{accl}} \tag{3}$$

where the tilt angles, pitch and roll, respectively denote $\theta_{accl}$ and $\varphi_{accl}$.

However, yaw is in the horizontal plane. It is orthogonal with gravity acceleration. So it is unable to get the projection on horizontal plane, namely, yaw cannot be calculated from the accelerometer.

In addition, the environment where the agricultural robot works is complex. And the motion of the agricultural robot itself is changed rapidly in real time. The high frequency measurement noise is included.

The gyroscope can measure the rotation rate of IMU. So the triaxial tilt angles $\Phi_{\text{Gyro}}$ , include roll, pitch and could be obtained via rotation rate integral by using (4).

$$\Phi_{\text{Gyro}} = \int \omega_{gyro} \cdot dt \tag{4}$$

where $\omega_{gyro}$ is the measured angular rate in each direction. And $t$ is the gyroscope measurement sapling period.

Because of the temperature variation, unstable moment of force and noise jamming which notes $\sigma$, the gyroscope will generate drift error which will become bigger and bigger with time, which can be seen in (5).

$$\Phi_{\text{Gyro}} = \int (\omega_{gyro} + \sigma) \cdot dt \tag{5}$$

According to the analysis above, the conclusion is that using accelerometer or gyroscope alone to calculate the attitude angle is not suitable. The accelerometer has motion bandwidth problem. The gyroscope has drift error with long time.

### *2.2 Sensor Fusion Method*

Sensor fusion is desirable on exerting the advantages of accelerometer and gyroscope. Here, we used Kalman filter to integrate the data from both accelerometer and gyroscope. Fig. 5 shows the block diagram of sensor fusion method processing.

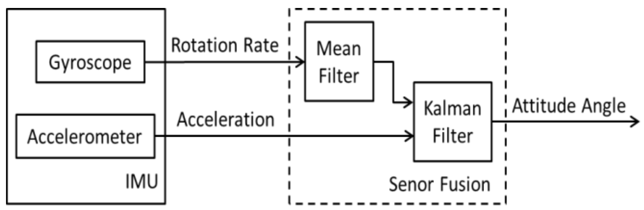



Fig. 5 Block diagram of sensor fusion method

The sensor fusion method includes a mean filter and a Kalman filter. For the outdoor application of agricultural robot, the high frequency measured noise will appear which not conform to the law of random process. So the mean filter is to get rid of the outlier signal as pre-process for angular rate from gyroscope in this low-cost IMU. This mean filter is expressed in (6).

$$\omega_{gyro} = \frac{\sum_{t=1}^{n} \omega_t}{n} \tag{6}$$

where $n$ is the window size of the mean filter. In consideration of the computing scale and time delay, n=3 in this research.

The Kalman filter is optimal when the process noise and the measurement noise can be modelized by white Gaussian noise (Mathieu et al, 2004). As mentioned earlier, the relationship between tilt angle and angular rate is derivative relations. The real tilt angle $\partial$ can be used to make a state equation as (7) and measurement equation as (8).

$$\begin{bmatrix} \dot{\partial} \\ \dot{\text{b}} \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \partial \\ b \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \omega_{Gyro} + \begin{bmatrix} \sigma_{Gyro} \\ 0 \end{bmatrix} \tag{7}$$

$$\partial_{Accl} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \partial \\ b \end{bmatrix} + \sigma_{Accl} \tag{8}$$

where $\omega_{Gyro}$ is the angular rate with bias, $\partial_{Accl}$ is the angle calculated from accelerometer by using (2), (3) and (6) via mean filter, $\sigma_{Gyro}$ is the measurement noise of gyroscope, $\sigma_{Accl}$ is the measurement noise of accelerometer, and $b$ is the drift error of gyroscope. $T_s$ is set up as system sampling period. Equation (9) is the state equation of the discrete-time system.

$$\text{X(k | k-1)} = \text{A} \cdot \text{X(k-1 | k-1)} + \text{B} \cdot \text{U(k)} \tag{9}$$

where $A$ is system transition matrix $A = \begin{bmatrix} 1 & Ts \\ 0 & 1 \end{bmatrix}$, $B$ is system control matrix $B = \begin{bmatrix} Ts \\ 0 \end{bmatrix}$, *X(k|k-1)* is the system state in moment k estimated by state k-1. *U(k)* is exogenous control input in moment k. *P(k|k-1)* is the priori estimate error covariance of *X(k|k-1)* as (10).

$$\text{P(k | k-1)} = \text{A} \cdot \text{P(k-1 | k-1)} \cdot \text{A}^{\text{T}} + Q \tag{10}$$

where $Q$ is covariance matrix of system process noise $Q = \begin{bmatrix} q\_accl & 0 \\ 0 & q\_gyro \end{bmatrix}$, which $q\_accl$ is the covariance of accelerometer and $q\_gyro$ is the covariance of gyroscope. Matrix $\text{A}^{\text{T}}$ is the transpose of matrix $A$.

The optimal estimate *X(k | k)* in state *k* is calculated by using (11)

$$X(\text{k | k}) = \text{X(k | k-1)} + k_g(\text{k}) \cdot (Z(\text{k}) - \text{H} \cdot \text{X(k | k-1)}) \tag{11}$$

where $H$ is observation matrix, H=[1 0]. $k_g(k)$ is Kalman gain derived from minimizing the posteriori error covariance by using (12).

$$\text{k}_\text{g}(\text{k}) = \text{P(k | k-1)} \cdot \text{H}^\text{T} / (\text{H} \cdot \text{P(k | k-1)} \cdot \text{H}^\text{T} + \text{R}) \tag{12}$$

where $R$ is covariance matrix of measuring error from accelerometer. In order to make the Kalman filter update, we should update the covariance equation by using (13).

$$\text{P(k | k)} = (I - k_g(\text{k}) \cdot H) \cdot P(\text{k | k-1}) \tag{13}$$

where I is Unit matrix $I = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$.

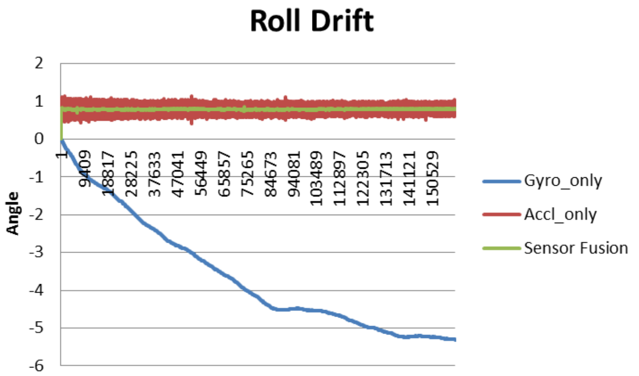
Above these, based on recursive functions from (8) to (12), keep calculating until finding the optimal estimate attitude angle value.

## 3. RESULTS AND DISCUSSION

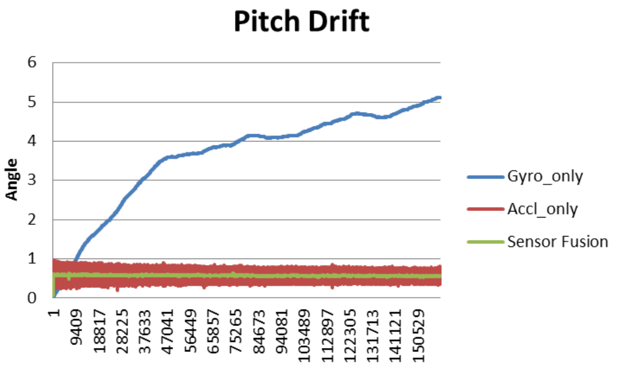
In order to verity the validity of the sensor fusion method via mean filter and Kalman filter better than one sensor, no matter which is used in attitude angle estimation, gyroscope or accelerometer, two parameters were chosen to analyse it. One was drift error and the other was dynamic attitude angle estimation.

### *3.1 Drift Error*

The drift error is directly related to the measurement accuracy and stability of the measurement system. Here, we compared the performances among gyroscope-only, accelerometer-only and sensor fusion integration by the two sensors. Fig. 6 shows the result of drift in 20 minutes. In the coordinate system, abscissa is the measurement sampling number in twenty minutes. Ordinate is the drift angle, with degree as the unit.




(a) Drift in roll direction

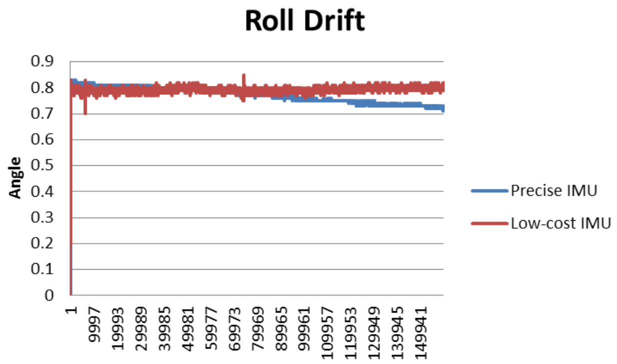



(b) Drift in pitch direction

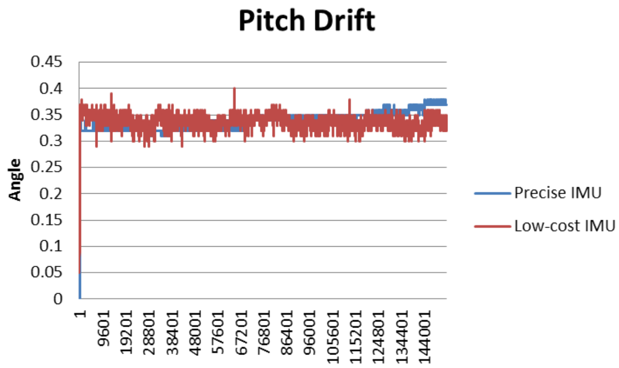
Fig. 6 Drift from gyroscope, accelerometer and sensor fusion

From Fig. 6, because of the integral error accumulation, the drift just measured by gyroscope increases continuously. Otherwise, the drift measured by accelerometer does not increased with time, but the drift oscillation is in one biggish area. Whereas, under sensor fusion method, the drift is almost zero. It is also smoother than the data from accelerometer.

It was found that the drift under sensor fusion method was superior to the other two single sensor methods. So, based on this sensor fusion method, we compared the drift performance between this low-cost IMU and a precise IMU manufactured by Japan Aviation Electronics Industry, Ltd, which can output attitude angles directly.




(a) Drift in roll direction




(b) Drift in pitch direction

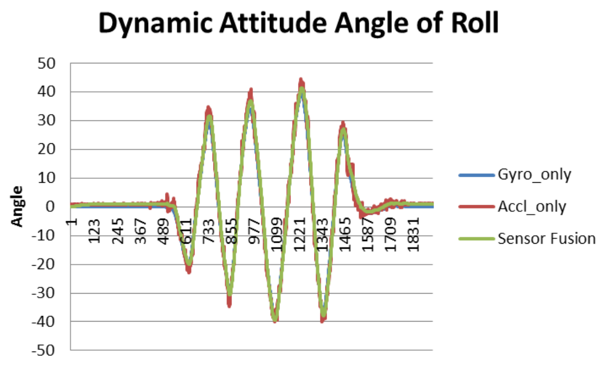
Fig. 7 Drift from the low-cost IMU and the precise IMU

The precise IMU and the low-cost IMU were fixed on the same plane and performed and logged the drift data. Fig.7 shows one result of the experiments. The drift data of these two IMUs is logged in 20 minutes. In the coordinate system, abscissa is the sampling number with time, ordinate is the drift angle, with degree as the unit. The reason why the output had a tiny angle is that we cannot guarantee the absolute level of the plane.

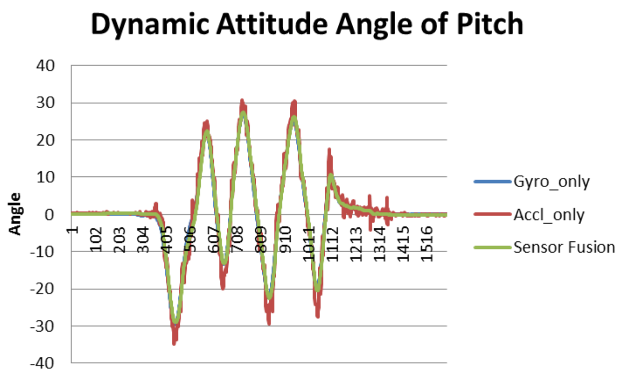
### *3.2 Dynamic Attitude Angle*

The IMU set up on the agricultural robot is used mainly for logging the attitude state and correcting the heading angle of the working agricultural robot. So the Dynamic characteristic of the IMU is very important to the agricultural robot navigation.

We logged the dynamic attitude angle data when rotated the low-cost IMU in different rotation directions. Fig.8 shows the dynamic attitude angle in roll direction and pitch direction. Because the IMU worked in random variable motion, we can see the dynamic curve measured by accelerometer is not stable, especially on the point when changing the motion direction. In a short time, the data drift from the gyroscope is not obvious. That is the reason why the dynamic curve measured by gyroscope is overlapped with the dynamic curve measured by sensor fusion method. However, the drift error will accumulate with time.




(a) Angle in roll direction




(b) Angle in pitch direction

Fig. 8. Dynamic attitude angle from gyroscope, accelerometer and sensor fusion

From Fig.8, we know that the data from sensor fusion method not only inherits the little drift characteristics from accelerometer, but also inherit the transient stability from gyroscope. Here, we compared the performance of dynamic attitude angle estimation between this low-cost IMU used sensor fusion method and that pre-mentioned precise IMU. In order to get the high precise comparison result, we designed to make the low-cost IMU and the precise IMU in one same centre of gravity. Fig 9 shows this situation.

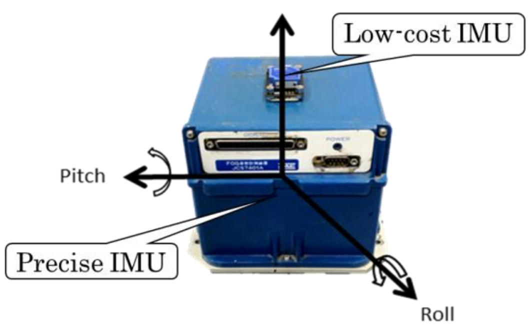
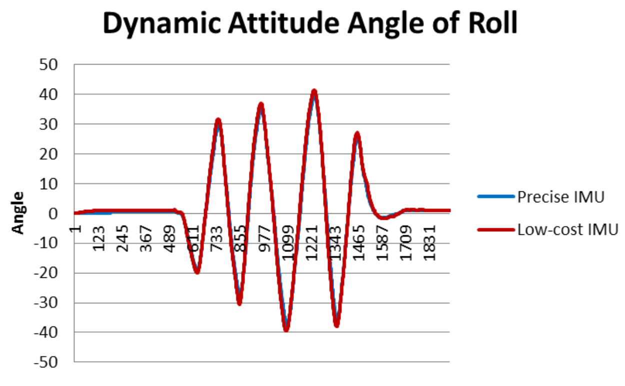
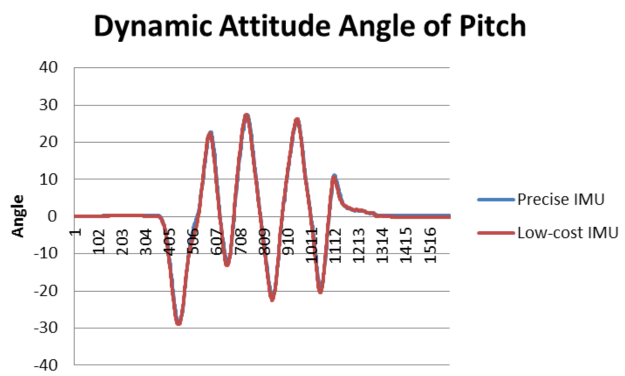



Fig. 9 Low-cost IMU and the precise IMU based comparison platform

Just as the approach used in comparing the dynamic angle estimation via gyroscope only, accelerometer only and sensor fusion method, we also rotate the low-cost IMU and the precise IMU together in different rotation directions and logged the data, which include roll direction and pitch direction. As mentioned above, yaw is in the horizontal plane. It is orthogonal with gravity acceleration. So it is unable to get the projection on horizontal plane, namely, yaw cannot be calculated from the accelerometer. So the method of Kalman filter cannot be applied to the yaw direction.




(a) Aangle in roll direction




(b) Angle in pitch direction

Fig. 10. Dynamic attitude angle from the low-cost IMU and the precise IMU

It shows that the dynamic attitude angle of the low-cost IMU coincides with the precise IMU very well in Fig. 10. The comparison result of dynamic attitude angle estimation was that the RMS error between the low-cost IMU and precise IMU was observed as 1.35 degree in roll direction and 0.73 degree in pitch direction. It is concluded that a low-cost IMU has acceptable performance of dynamic attitude angle estimation by using sensor fusion technology.

## 4. CONCLUSIONS

In this research, a sensor fusion technology combining a mean filter with a Kalman filter processed the data into attitude angle from a low-cost IMU for agricultural robot application. Based on this method, it compensated the IMU drift, improved the noise immunity and reduced the measurement error. At last, two parameters, drift error and dynamic attitude angle estimation, were chosen to compare with that of a precise IMU. The sensor fusion method is effective in attitude angle estimation.

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