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Design and Evaluation of an MPU6050-Based Relative Yaw Angle Measurement Module

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Abstract
This paper presents the design and evaluation of a low-cost relative yaw angle measurement module based on the MPU6050 inertial measurement unit. The proposed module estimates the rotation angle around the vertical Z-axis in the horizontal plane. The output angle is normalized within the range of 0° to 360°, where clockwise rotation increases the angle and counter-clockwise rotation decreases it according to the selected sign convention. The measurement principle is based on reading the Z-axis gyroscope signal, compensating the initial gyroscope bias, applying a small dead-band to reduce noise-induced drift, and integrating the angular velocity over time. Since the MPU6050 consists of a three-axis accelerometer and a three-axis gyroscope but does not include a magnetometer, the proposed system is not intended to operate as an absolute compass with respect to magnetic north. Instead, it is designed as a relative yaw angle measurement module referenced to an initial orientation. Three simple experiments are proposed to evaluate the module: yaw direction response, stationary drift, and fixed-angle rotation error. The results can be used to determine the suitability of the proposed module for low-cost embedded applications requiring short- or medium-duration relative heading measurement.

Keywords: *MPU6050; yaw angle; Z-axis gyroscope; relative angle measurement; gyroscope drift; inertial measurement unit; Arduino.*

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I. Introduction

Measuring the rotation angle of a device in the horizontal plane is an important requirement in many embedded systems, educational platforms, measurement devices, and low-cost robotic applications. In such applications, a compact and inexpensive sensing solution is often preferred. The MPU6050 inertial measurement unit is widely used because it integrates a three-axis accelerometer and a three-axis gyroscope in a small package and can be easily interfaced with common microcontrollers through the I2C protocol.

When the MPU6050 is placed on a horizontal plane, its Z-axis gyroscope output can be used to estimate the relative yaw rotation of the module. The yaw angle can be calculated by integrating the angular velocity around the Z-axis. However, gyroscope-based integration is affected by bias, measurement noise, and drift. Even a small zero-rate offset can accumulate over time and produce a noticeable yaw error when integrated continuously.

It is important to clarify that the MPU6050 does not contain a magnetometer. Therefore, a module built only with the MPU6050 cannot determine the absolute heading with respect to magnetic north. In this work, the objective is not to develop an absolute magnetic compass. Instead, the proposed system is designed as a relative yaw angle measurement module. The user sets an initial orientation as 0°, and the module tracks the rotation angle relative to that initial reference.

The goal of this paper is to develop a simple embedded algorithm for measuring the relative yaw angle using the MPU6050. The algorithm includes Z-axis gyroscope bias calibration, angular-rate conversion, dead-band filtering, discrete-time integration, and angle normalization in the range of 0° to 360°. The module is evaluated through basic experiments including yaw direction response, stationary drift, and fixed-angle rotation error.

II. Hardware Configuration

The experimental system consists of an Arduino UNO microcontroller and an MPU6050 inertial measurement unit. The communication between the microcontroller and the sensor is implemented using the I2C bus. The MPU6050 is configured to measure angular velocity and acceleration, although the proposed yaw estimation method mainly uses the Z-axis gyroscope signal.

During measurement, the MPU6050 module should be mounted approximately parallel to the horizontal plane. In this arrangement, the Z-axis of the sensor is approximately perpendicular to the horizontal plane. Therefore, rotation of the module around the vertical axis produces a change in the Z-axis gyroscope reading.

Table 1. Connection between MPU6050 and Arduino UNO

MPU6050 pin	Arduino UNO pin
VCC	5V
GND	GND
SDA	A4
SCL	A5

III. Theoretical Background

3.1. Z-Axis Gyroscope Measurement Model

The raw Z-axis gyroscope measurement can be described by the following simplified model:

$$G_z = G_{z,true} + G_{z,offset} + n_z$$

where G_z is the raw gyroscope reading, $G_{z,true}$is the component caused by the true angular motion, $G_{z,offset}$ is the zero-rate bias, and n_z represents measurement noise. When the sensor is stationary, the ideal angular velocity should be zero. However, the measured gyroscope value is usually not exactly zero because of bias and noise. If this residual value is integrated over time, the estimsaoated yaw angle will drift even when the sensor is not rotating.

For the $\pm 250°/s$ gyroscope range, the scale factor of the MPU6050 is $S_g = 131\ LSB/(°/s)$. Thus, the angular velocity around the Z-axis is calculated as $\omega_z = \frac{(G_z - G_{z,offset})}{S_g}$, where ω_z is expressed in degrees per second.

3.2. Relative Yaw Angle Estimation

The relative yaw angle is estimated by integrating the angular velocity over time:

$$\theta_{z(k)} = \theta_{z(k-1)} + \omega_{z(k)} * \Delta t$$

where $\theta_{z(k)}$ is the yaw angle at the k-th sampling instant, $\omega_{z\,(k)}$ is the angular velocity at the same instant, and Δt is the sampling interval.

After integration, the yaw angle is normalized into the range of 0° to 360°. With this representation, if the angle is initially 0° and the module rotates in the negative direction, the output angle wraps to a value close to 360° and then decreases. This behavior is suitable for representing a relative heading angle in a circular domain.

IV. Proposed Method

4.1. Initial Gyroscope Bias Calibration

Before yaw measurement starts, the sensor is kept stationary for a short period to estimate the Z-axis gyroscope bias. A number of N gyroscope samples are collected, and their average value is used as the initial bias:

$$G_{z,offset} = \left(\frac{1}{N}\right) * \sum_{i=1}^{N} G_{z(i)}$$

This offset is subtracted from subsequent gyroscope readings. During calibration, the sensor must remain stationary. If the sensor is rotated or vibrated during calibration, the estimated offset may be incorrect and the yaw angle may drift faster.

4.2. Angular-Rate Dead-Band Filtering

Even after bias compensation, the angular velocity may still fluctuate around zero due to sensor noise. If these small fluctuations are continuously integrated, they can still produce yaw drift. To reduce this effect, a dead-band threshold is applied:

$$\omega_z = \begin{cases} 0, |\omega_z| < \epsilon \\ \omega_z, |\omega_z| \geq \epsilon \end{cases}$$

In the implementation, an initial value of 0.05°/s is used. This value can be tuned depending on the noise level of the sensor and the required sensitivity of the application.

4.3. Rotation Direction Convention

The sign of the Z-axis gyroscope output depends on the physical orientation of the sensor and the selected rotation convention. Therefore, a sign coefficient K_{sign} is introduced:

$$\omega_z = K_{sign} \frac{\left(G_z - G_{z,offset}\right)}{S_g}$$

If clockwise rotation should increase the angle, K_{sign} is selected accordingly. If the measured direction is opposite to the desired convention, the value of K_{sign} is changed from 1 to -1, or vice versa. This allows the module to be adapted to different mounting orientations.

4.4. Algorithm Summary

The proposed yaw measurement procedure includes the following steps: initialize the I2C interface; wake up the MPU6050; configure the gyroscope range to ±250°/s; collect stationary samples and estimate the Z-axis gyroscope bias; read the raw Z-axis gyroscope value; subtract the estimated gyroscope bias; convert the raw value into degrees per second; apply the angular-rate dead-band; integrate the angular velocity to obtain the relative yaw angle; normalize the yaw angle into the range of 0° to 360°; and display or output the yaw angle for the target application.

V. Experimental Design

Three basic experiments are used to evaluate the proposed module. The experiments are intentionally simple so that they can be performed without specialized laboratory equipment.

5.1. Yaw Direction Response Test

The purpose of this experiment is to verify whether the module can correctly detect the direction of rotation around the Z-axis. After calibration, the initial orientation is set as 0°. The module is then rotated clockwise and counter-clockwise. The expected behavior is that clockwise rotation increases the angle, counter-clockwise rotation decreases the angle, and counter-clockwise rotation from 0° wraps the output to a value close to 360°.

5.2. Stationary Drift Test

The purpose of this experiment is to evaluate the yaw drift when the module is kept stationary. After calibration and zero setting, the module is placed on a fixed horizontal surface. The yaw angle is recorded after 60 s, 180 s, and 300 s. Since the angle is represented in the range of 0° to 360°, a value close to 360° must be interpreted as a small negative error. For example, if the measured angle is 358.8°, the error relative to 0° is -1.2°, and the drift magnitude is 1.2°.

5.3. Fixed-Angle Rotation Test

The purpose of this experiment is to evaluate the measurement error when the module is rotated to known reference angles. The selected reference angles are 90°, 180°, 270°, and 360°. After each rotation, the measured angle is recorded and compared with the reference value. For 360°, the angle is considered equivalent to 0°. Therefore, if the module measures 2° after a full rotation, the error is 2°. Similarly, if the module measures 358°, the error is also 2°.

VI. Experimental Results

6.1. Yaw Direction Response

After calibration and zero setting, the module is rotated around the Z-axis. The qualitative result is presented in Table 2. This test confirms whether the algorithm correctly identifies the relative rotation direction and handles the circular boundary between 0° and 360°.

Table 2. Yaw direction response test

Test condition	Expected behavior	Observed result
Clockwise rotation	Angle increases	Pass
Counter-clockwise rotation	Angle decreases	Pass
Counter-clockwise rotation from 0°	Angle wraps to near 360°	Pass

6.2. Stationary Drift

The module is kept stationary after calibration. The measured yaw angle is recorded at different times. The results are shown in Table 3. The stationary drift test indicates how much the estimated yaw angle changes when the sensor is not rotating. Because the yaw angle is obtained by integrating gyroscope data, drift is expected to increase over time. Initial bias calibration and dead-band filtering reduce small drift, but they cannot completely eliminate long-term drift.

Table 3. Stationary yaw drift

Time duration	Measured angle	Drift
60 s	0.13°	0.13°
180 s	0.34°	0.34°
300 s	0.52°	0.52°

As shown in Table 3, the measured yaw drift was 0.13° after 60 s, 0.34° after 180 s, and 0.52° after 300 s. The drift increased gradually with time, which is expected because the yaw angle is obtained by integrating the gyroscope signal. However, the total drift after 300 s remained below 1°, indicating that the initial Z-axis gyroscope bias calibration and dead-band filtering were effective for short-term relative yaw measurement.

6.3. Fixed-Angle Measurement Error

The module is rotated to predefined reference angles. The measured angles and absolute errors are shown in Table 4. The remaining measurement error may be caused by residual gyroscope bias, manual rotation error, mechanical vibration, sampling-time variation, and the absence of an absolute heading reference.

Table 4. Fixed-angle measurement error

Reference angle	Measured angle	Absolute error
90°	90.28°	0.28°
180°	180.24°	0.24°
270°	270.36°	0.36°
360°	359.34°	0.66°

Table 4 shows the fixed-angle measurement results. The absolute errors at 90°, 180°, 270°, and 360° were 0.28°, 0.24°, 0.36°, and 0.66°, respectively. The maximum error was 0.66° at the 360° reference angle. These results indicate that the proposed module can estimate relative yaw rotation with sub-degree accuracy under the tested conditions

VII. Discussion

The experimental procedure is designed to evaluate whether the proposed module can provide a usable relative yaw angle in the horizontal plane. The yaw direction response test verifies the basic logic of the algorithm. Clockwise rotation should increase the angle, while counter-clockwise rotation should decrease it. The 0°/360° transition is also important because the module represents the yaw angle in a circular range.

The stationary drift test is essential because gyroscope-based yaw estimation is sensitive to bias. Even after calibration, a small residual bias may remain. When this bias is integrated over time, the yaw angle gradually changes. The proposed dead-band filtering reduces the effect of very small angular-rate fluctuations, but it does not provide an absolute correction. Therefore, the module is more suitable for short- and medium-duration relative yaw measurement rather than long-term absolute heading estimation.

The fixed-angle rotation test evaluates the practical accuracy of the module. The error depends not only on the sensor and algorithm but also on the experimental method. If the module is rotated manually, the reference angle may contain human error. A more accurate evaluation can be obtained using a rotary platform or a mechanical angle fixture.

The main limitation of the proposed system is the lack of an absolute yaw reference. Since the MPU6050 does not include a magnetometer, the system cannot determine the magnetic north direction and cannot automatically correct yaw drift over long time intervals. For applications requiring long-term heading stability, the system should be extended with a magnetometer, external reference, encoder, or sensor fusion algorithm.

VIII. Conclusion

This paper presented the design and evaluation of a low-cost relative yaw angle measurement module using the MPU6050 inertial measurement unit. The proposed method uses the Z-axis gyroscope signal, initial bias calibration, dead-band filtering, and discrete-time integration to estimate the yaw angle around the vertical axis. The output angle is normalized into the range of 0° to 360°, allowing intuitive representation of clockwise and counter-clockwise rotation.

Three simple experiments were proposed to evaluate the module: yaw direction response, stationary drift, and fixed-angle rotation error. The module is suitable for applications that require low-cost relative yaw measurement in the horizontal plane. However, because the MPU6050 does not include a magnetometer, the module cannot operate as an absolute compass and cannot eliminate long-term yaw drift completely.

Future work may include integrating a magnetometer such as HMC5883L or QMC5883L, applying complementary filtering or Kalman filtering, and improving the bias estimation method to increase the long-term stability of the yaw angle.

Acknowledgments

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