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In-Vehicle MEMS IMU Calibration Using Accelerometer

Piyatap Promrit #1, Somphop Chokchaitam #2, Masami Ikura #3

R&D section,
Toyota Tsusho Nexty Electronics (Thailand) Co., Ltd.
Bangkok, Thailand.

1piyatap@th.nexty-ele.com, 2somphop@th.nexty-ele.com, 2ikura@th.nexty-ele.com

***Abstract*—This paper demonstrates how we can compensate the installation errors (roll and pitch angles) by estimating the rotation of the installed IMU. The estimated rotation is then used to compensate the IMU. This is result in better IMU accuracy.**

Keywords—MEMS, IMU, calibration, in-vehicle, accelerometer

I. Introduction

IMU plays the important roles of localization of the current vehicle position in many system form vehicle monitoring [1] to autonomous driving vehicle [2], [3]. The problem is MEMS IMU has to calibrate in order to get accurate measurement output. Though MEMS IMU is calibrated, in the installation processes some errors from screw wrenching and installation location, MEMS IMU cannot be installed perfectly to the same plane at the calibration (x-y axis plane perpendicular to gravity force, or bubble level) the result of the installation can be shown as Figure 1.

Figure 1 In-Vehicle Installation error ϕ in roll and θ in pitch angles

This paper used 6-Axis IMU which contains 3-Axis accelerometer and 3-Axis gyroscope. But only the accelerometer output is used. In the next section, the basic rotation matrices used estimating the error for roll and pitch angles is explained.

II. Rotation Matrix in Three Dimensions

This section explains the rotation matrix used in this paper.

A. Basic Rotations

The roll, pitch and yaw rotation matrices, which transform a vector (such as the earth's gravitational field vector g) under a rotation of the coordinate system by angles ϕ in roll, θ in pitch and ψ in yaw about the x, y and z axes respectively, are

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \tag{1}$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \tag{2}$$

$$R_z(\psi) = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

For column vectors, each of these basic vector rotations appears counterclockwise when the axis about (which they occur) points toward the observer, the coordinate system is right-handed, and the angle is positive.

R_z, for instance, would rotate toward the y-axis a vector aligned with the x-axis, as can easily be checked by operating with R_z on the vector (1, 0, 0) shown as Figure 2.

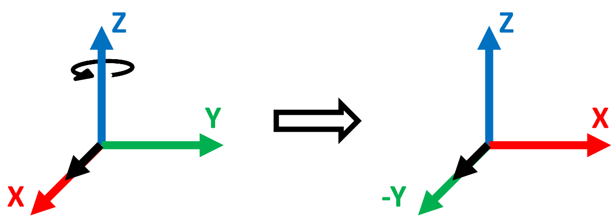

Figure 2 Rotate the z-axis (90°)

Figure 2 show the example of rotation counterclockwise the z-axis (90°) on the vector (1, 0, 0), calculation method using rotation matrix shown as below.

$$R_z(90°)\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos 90° & \sin 90° & 0 \\ -\sin 90° & \cos 90° & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$
$$= \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$$

B. General rotations

Other rotation matrices can be obtained from these three using matrix multiplication. Rotations whose roll, pitch, and yaw angles are ϕ, θ, ψ respectively. More formally, it is an intrinsic rotation angles are ϕ, θ, ψ about axes x, y, z respectively.

Similarly, the product:

$R_{xyz} = R_x(\phi)\, R_y(\theta)\, R_z(\psi)$

and $R_{yxz} = R_y(\theta)\, R_x(\phi)\, R_z(\psi)$

III. Roll and Pitch Estimation

In this section, how to estimate roll and pitch installation error is shown. Only roll and pith will be estimate, since the information from accelerometer cannot estimate yaw angle, because yaw rotation is perpendicular to gravity force.

Assuming IMU lies on flat surface, the measured output 1g on Z-Axis and 0g on X-Axis and Y-Axis.

For R_{xyz} rotation:

$$R_{xyz} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = R_x(\phi) R_y(\theta) R_z(\psi) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (4)$$

$$R_{xyz} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix}$$

$$\begin{bmatrix} G_x \\ G_y \\ G_z \end{bmatrix} = \begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix} \quad (5)$$

From equation (5), roll ϕ angle can be solved as

$$\frac{G_y}{G_z} = \frac{\cos\theta\sin\phi}{\cos\theta\cos\phi}$$
$$\frac{G_y}{G_z} = \frac{\sin\phi}{\cos\phi}$$
$$\frac{G_y}{G_z} = \tan\phi$$
$$\phi = \tan^{-1}\left(\frac{G_y}{G_z}\right) \quad (A)$$

From equation (5), pitch ϕ angle can be solved as

$$\frac{-G_x}{\sqrt{{G_y}^2 + {G_z}^2}} = \frac{\sin\theta}{\sqrt{\cos^2\theta\sin^2\phi + \cos^2\theta\cos^2\phi}}$$
$$\frac{-G_x}{\sqrt{{G_y}^2 + {G_z}^2}} = \frac{\sin\theta}{\sqrt{\cos^2\theta\,(\sin^2\phi + \cos^2\phi)}}$$
$$\frac{-G_x}{\sqrt{{G_y}^2 + {G_z}^2}} = \frac{\sin\theta}{\sqrt{\cos^2\theta}}$$
$$\frac{-G_x}{\sqrt{{G_y}^2 + {G_z}^2}} = \frac{\sin\theta}{\cos\theta}$$
$$\frac{-G_x}{\sqrt{{G_y}^2 + {G_z}^2}} = \tan\theta$$
$$\theta = \tan^{-1}\left(\frac{-G_x}{\sqrt{{G_y}^2 + {G_z}^2}}\right) \quad (B)$$

For R_{yxz} rotation, by using similar method as above we get

$$\phi = \tan^{-1}\left(\frac{G_y}{\sqrt{{G_x}^2 + {G_z}^2}}\right) \quad (C)$$
$$\theta = \tan^{-1}\left(\frac{-G_x}{G_z}\right) \quad (D)$$

The order of rotation can be R_{xyz} or R_{yxz}, we can try both rotation and see if which rotation give better result or choose R_{xyz} rotation when

$$\left|\sqrt{{G_y}^2 + {G_z}^2} - 1\right| < \left|\sqrt{{G_x}^2 + {G_z}^2} - 1\right| \quad (6)$$

Otherwise, choose R_{yxz} rotation.

IV. Roll And Pitch Angle Compensation

After Roll and Pitch angle are estimated from last section. The estimated Roll and Pitch angle will be applied to compensate the output using rotation matrix. Yaw angle is assumed as 0 since it cannot be estimated using only information from accelerometer.

For R_{xyz} rotation:

$$R_{xyz} = R_x(\phi) R_y(\theta) R_z(0)$$
$$R_{xyz} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ \sin\phi\sin\theta & \cos\phi & \sin\phi\cos\theta \\ \cos\phi\sin\theta & -\sin\phi & \cos\phi\cos\theta \end{bmatrix}$$

For R_{xyz} rotation:

$$R_{yxz} = R_y(\theta) R_x(\phi) R_z(0)$$
$$R_{yxz} = \begin{bmatrix} \cos\theta & \sin\theta\sin\phi & -\sin\theta\cos\phi \\ 0 & \cos\phi & \sin\phi \\ \sin\theta & -\cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix}$$

This rotation matrix is applied to obtain compensated measured value in below equation.

$$K_a\tilde{a} = R(I + S_a + M_a)a + b_a$$

Where

$K_a\tilde{a}$ is measured output of accelerometer

R is rotation matrix

S_a is the accelerometer scale factor matrix

M_a is the accelerometer cross coupling matrix

b_a is accelerometer bias error

S_a, M_a and b_a can be calculated using method available in [4]

V. EXPERIMENT RESULT

The experiment is using InvenSense MPU6050. The unit is mounted on an Arduino board. The unit can be seen in Figure 3. The unit is calibrated to obtain compensate value. The compensated value from this step is applied to IMU output. Then the calibrated IMU is put on 2 lamps which has slope of 30° and 15° on Roll angle and Pitch angle respectively. The setup can be seen in Figure 4.

The output is read from accelerometer 300 times then average to eliminate the noise. Then the rotation order is selected. The average output of accelerometer on X-Axis, Y–Axis and Z-Axis are input to determine the order of rotation using equation (6).

$$\left|\sqrt{G_y{}^2 + G_z{}^2} - 1\right| = \left|\sqrt{0.4937^2 + 0.8330^2} - 1\right| = 0.03168771$$

$$\left|\sqrt{G_x{}^2 + G_z{}^2} - 1\right| = \left|\sqrt{-0.2235^2 + 0.8330^2} - 1\right| = 0.197543$$

So, R_{xyz} rotation is selected in this case.

Figure 3 Arduino board and InvenSense MPU6050

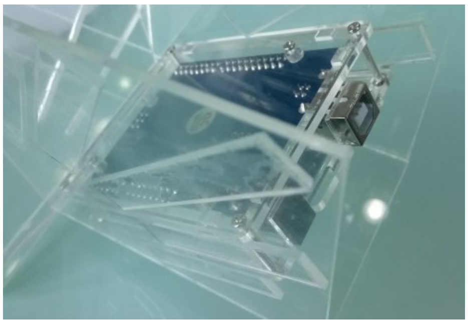

Figure 4 30° on Roll angle and 15° on Pitch angle setup

Roll estimation and Pitch estimation can be done using equation (A) and equation (B) respectively.

Roll estimation; $\phi = \tan^{-1}\left(\frac{G_y}{G_z}\right) = 30.6532°$

Pitch estimation; $\theta = \tan^{-1}\left(\frac{-G_x}{\sqrt{G_y{}^2+G_z{}^2}}\right) = 12.9997°$

The correctness of the estimation is 99.978% for Roll estimation and 86.66% for Pitch estimation. Then the estimated Roll angle and Pitch angle are applied to measure the acceleration output on X-Axis, Y-Axis and Z-Axis. The output is shown in Figure 5. The expected accelerometer output for X-Axis, Y-Axis and Z-Axis are 0, 0 and 1 respectively.

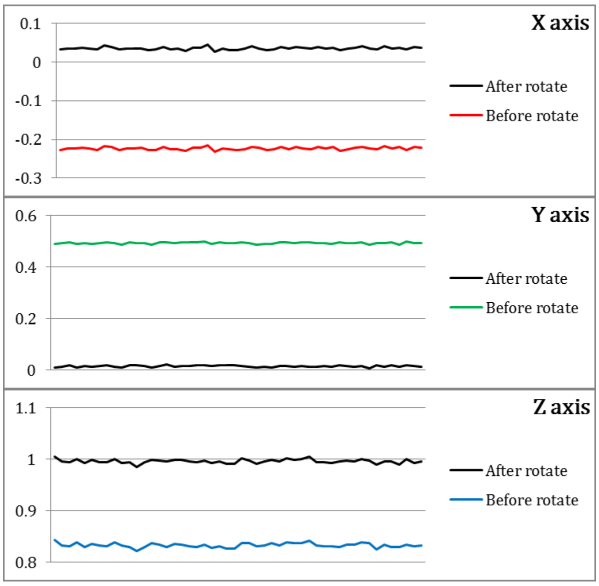

Figure 5 Accelerometer output before and after calibration

VI. CONCLUSION

An in-vehicle calibration method is presented in this paper. The calibration method used only the output from accelerometer. This method can compensate the installation error on Roll and Pitch angle. The calibrated accelerometer output shows promising improvement over uncalibrated output of the same MEMS IMU.

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