Implementation of PIC Based Vehicle’s Attitude Estimation System Using MEMS Inertial Sensors and Kalman Filter

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Abstract- In this paper, one dimensional drift free attitude estimation system using accelerometer and gyroscope was studied. The proposed system fuses data from accelerometers and gyroscopes by means of a Kalman filter. A PIC microcontroller is used for estimating the angle value in the proposed system. Moreover, this controller does all data acquisition and interfacing tasks. The experimental results are given to verify the proposed microcontroller based estimation system.

Keywords- accelerometer, gyroscope, Kalman filter, microcontroller, sensor data fusion, tilt angle estimation

I. INTRODUCTION

The estimation of the “tilt” of vehicles has been of much interest, especially in the areas such as aerospace [5] or control system [3],[6]. For instance, controlling autonomous flight vehicle is the practical issue related with tilt estimation. They have been utilized in applications such as forest fire perimeter tracking, military tactical reconnaissance, and rural search and rescue where rapid area searches are desired.

Guidance and navigation are the key technologies for the autonomous flight vehicle wherein the attitude information is indispensable. Inertial sensors fabricated by micro electromechanical system (MEMS) technology offer revolutionary improvements in cost, size, and ruggedness relative to fiber optic and spinning mass technologies. MEMS gyroscopes and accelerometers are ideal as components of a compact and affordable attitude determination system.

Gyroscopes measure the body’s angular velocity and, by integrating this angular velocity, they can calculate the attitude angle. Accelerometers measure the body’s translational acceleration. If they measure only the acceleration of gravity, they provide the body’s absolute attitude in the navigational frame of reference.

One drawback of the accelerometer is that its sensitiveness to vibration of bodies; vibration contains a lot of acceleration components. To reduce high frequency vibration noises, a low pass filter is required. This limits the bandwidth of the accelerometer and a phase delay is introduced in the filtered result. However,
calculating the attitude angle using the integrating gyroscope's output causes divergence in the attitude’s error.

In this paper, a microcontroller based attitude estimation system is implemented by using MEMS inertial sensors and Kalman filter. The proposed circuit diagram is shown in Fig.1.

![Proposed circuit diagram of PIC based attitude estimation system](image)

Fig. 1 Proposed circuit diagram of PIC based attitude estimation system

II. INTRODUCTION TO MEMS INERTIAL SENSORS

In this paper, two low-costs MEMS inertial sensors, ADXL202 and ENC-03J, are used.

ADXL202 is a dual axis accelerometer from Analog Device. It produces two PWM signals for each axis and the user can define the frequency of these PWM signals by selecting the value of $R_{\text{set}}$. In this paper, this frequency is chosen as 600Hz.

ENC-03J is a gyroscope from Murata. The bandwidth of the gyroscope operation can be defined by varying the cutoff frequency of lowpass and highpass filter. These filters are used at the output of the sensor.

III. ATTITUDE ESTIMATION ALGORITHM

The Kalman filter is a good tool that estimates the state of the system including measurement noise. It is useful to combine two sensor data containing measurement noise. Designing a Kalman filter requires a linear dynamic system model [1],[2],[4]-[6], like equation (1).

$$\dot{x} = A\dot{x} + W$$
$$y = C\dot{x} + V$$

(1)

For a microcontroller based one dimensional system, the state variable is defined as

$$x = \begin{bmatrix} \theta \\ b \end{bmatrix}$$

(2)

where, $\theta$ is the tilt angle and $b$ is the gyroscope bias.

The first derivative of the system with respect to time is shown in equation (3).

$$\dot{x} = \begin{bmatrix} \dot{\theta} \\ \dot{b} \end{bmatrix}$$

(3)

The matrix $A$ is the Jacobian matrix of the state derivative as shown in equation (4).

$$A = \begin{bmatrix} \frac{d\dot{\theta}}{d\theta} & \frac{d\dot{\theta}}{db} \\ \frac{db}{d\theta} & \frac{db}{db} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

(4)

The matrix $C$ is the Jacobian matrix of the measurement value as shown in equation (5).

$$C = \begin{bmatrix} \frac{d\theta}{d\theta} & \frac{d\theta}{m} \\ \frac{db}{db} & \frac{db}{db} \end{bmatrix}$$

$$= [0, 0]$$

(5)

The estimated tilt angle can be computed by using Kalman equations. These equations are shown in equation (6)-(10).

$$\dot{P} = AP + PA^T + Q$$
$$P = \dot{P} \times dt$$
$$K_{k+1} = P_kK_k(CP_k + R)^{-1}$$
$$P_{k+1} = P_k - K_{k+1}CP_k$$
$$\hat{x} = K_{k+1} \times \text{angle error}$$

(6)-(10)
where, $P$ is the error covariance matrix, $Q$ is the process noise covariance matrix and $R$ is the measurement noise covariance matrix. Angle error is obtained by subtraction the measured angle value of gyroscope from that of accelerometer.

The software flow chart of the main program of PIC is described in Fig 2. Accelerometer outputs are measured by using timer 0 of the PIC. But measuring gyroscope’s output required analog to digital conversion. The PIC16F877A has a built-in analog to digital convertor which has 10 bits resolution.

Timer 1 interrupt of PIC is used to define the sampling period of the system that is whenever the timer 1 interrupt occurs the PIC does all measuring and estimating tasks. Firstly, the PIC reads data from MEMS inertial sensors and stores these data in its internal memory for further computations.

The PIC measures x-axis duty cycle value ($T_{1x}$), y-axis duty cycle value ($T_{1y}$), and the period ($T_2$) from accelerometer duty cycle output. Then it computes angle information by using following equations [11]:

$$Y_{act} = \frac{Y_{cal} \times T_2}{T_{2, cal}}$$  \hspace{1cm} (11)

$$\text{angle} = \frac{K(T_{1y} - Y_{act})}{T_2}$$  \hspace{1cm} (12)

Where,

$Y_{cal}$ = y-axis duty cycle value at zero degree

$T_{2, cal}$ = the value of period at zero degree

$K$ = scale factor
Next, the PIC computes the angular velocity information by using gyroscope output [12].

$$\omega = \frac{(V_{\text{out}} - V_0)}{S_v}$$  \hspace{1cm} (13)

Where,

$\omega =$ angular velocity

$V_{\text{out}} =$ sensor output voltage

$V_0 =$ static output at zero angular velocity

$S_v =$ scale factor

All these calculations are carried out in the Conversion subroutine. The angular velocity information is then used to predict the current angle value. This is done by using Time update subroutine. The software flow chart of time update routine is described in Fig.3. In this routine, gact is the actual angular velocity, gmeas is the measured value of angular velocity, gbias is the gyroscope constant bias, and gangle is the computed angle value. The angle value is obtained by multiplying the actual angular velocity with sampling period (dt).

![Fig. 3 Flow chart of time update routine](image)

The flow chart of measurement update routine is also described in Fig.4. This routine produces estimation value of tilt angle at the present time by updating previous estimation value with the help of accelerometer measurement value. In this routine, acc_angle is the computed angle value by using accelerometer. Angle error is obtained by subtracting the two different angle values of accelerometer measurement and gyroscope measurement. The Kalman filter equations are applied to get estimated angle value. This value is then sent to the computer via serial communication for further processing.

![Fig. 4 Flow chart of measurement update routine](image)

**IV. EXPERIMENTS**

By using low-cost MEMS sensors in section II and Kalman filter algorithm in section III, tilt angle estimation system hardware is implemented as shown in Fig.5. The constructed system and its testing equipment are shown in Fig 5. The sampling frequency of this system is 100Hz and a PIC16F877A microcontroller is used as kernel for this system.
The results of tilt angle measurements by using ADXL202, ENC-03J and Kalman filter are shown in Fig 6, Fig 7, and Fig 8 respectively. From the values of the results, the Kalman filter can reduce the drift effect of the gyroscope as well as it can also reduce the vibration effect.

In order to verify the performance of the constructed system, a comparative study between a commercial IMU of MTI-G from XSENS and the proposed system is carried out. When the same input is applied to both systems, the output of the proposed system is very close to the output of the MTI-G in the range from -50 degree to +50 degree.

**V. CONCLUSIONS**

In this paper, a PIC microcontroller based attitude estimation system is described. Two low-costs inertial sensors and a microcontroller are used in the system. According to the results of testing, the constructed system outputs reliable tilt angle information during the range from -50deg to +50deg and the angular velocity less than ±90deg/s. This range is adequate for the stability control system of an aircraft.

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