Adaptive tuning of a Kalman filter using Fuzzy logic for attitude reference system

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Abstract: This paper proposed parameter control method for covariance of Kalman filter using fuzzy logic. Most people use accelerometer and gyro for calculating attitude and Kalman filter for fusion algorithm of two sensors. However, parameter of Kalman filter isn't correctly predicted and attitude reference system (ARS) using Kalman filter which has non-controlled parameter has many errors when it is moved a great variation. For improving this problem, we proposed parameter of Kalman filter tuning method using fuzzy logic and then we compared our ARS module with Crossbow Nav420CA.

Keywords: ARS, Kalman filter, Fuzzy logic, Accelerometer, Gyro, Euler angle**.**

I. INTRODUCTION

Recently, the development in micro-electro-mechanical system (MEMS) technology has made it possible to make cheap chip like accelerometer and gyro sensors, which have been adopted into many applications but traditionally inertial sensors have been too costly [1-2]. Attitude reference system (ARS) estimates body's roll and pitch. It is widely used in robot, aircraft, ship and so on. Particularly, there is getting popular robot market. Humanoid and military robots have been interesting topics for the past decade. Therefore, inexpensive and high efficient attitude sensor is necessary for an effective attitude control [2].

Most of the ARS is consist of accelerometer and gyro. Accelerometer measures acceleration of the body and gyro measures angular rate of the body. Before time, attitude calculation is possible by simple integration using gyro. However, there is difficult to attitude calculation as using low cost MEMS sensors because of accumulated error of output. Therefore, there is recently study about calibrated method of gyro error using accelerometer. Fusion method of two different sensors uses widely Kalman filter [2-3]. But it has trend that unstable filter by parameter of Kalman filter which is difficult to estimate. We had known through experiment that if variation of accelerometer is large then Kalman filter error is large. Using this fact, this paper proposed calibration method that controls parameter of Kalman filter using fuzzy logic.

II. ATTITUDE DETERMINATION FROM EACH SENSOR

1 Attitude determination from gyro

The roll($\varnothing$), pitch(θ), yaw(ψ) rate of the body are measured using gyro and accelerometer. We need to consider its body axis system so that we can calculate attitude. Attitude calculation method is divided into quaternion method, cosine matrix method and Euler angle method. Among these methods, we used Euler angle method because it can easily recognize user to attitude of the body. The following equation is direction cosine matrices of each axis [3-4].

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

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

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

The transformation from reference frame to body frame can be represented in Fig. 1. Therefore, the relation between gyro output and Euler angles can be described using (1)-(3) as follows :

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix} + C_x \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + C_x C_y \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} \tag{4}$$

where each ω_x, ω_y, ω_z are the gyro outputs in the x, y, z axis. We get next term by applying the Euler angles to gyro output.

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{5}$$

This paper proposed ARS development so that $\dot{\phi}$ and $\dot{\theta}$ is only used.

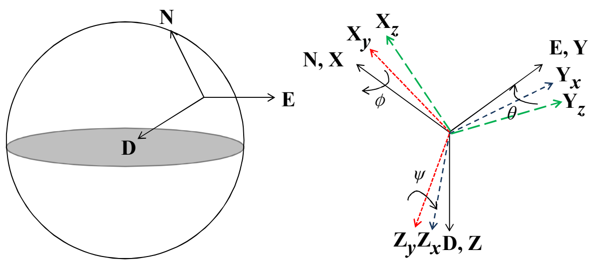

Fig.1. Definition of Euler angle

2. Attitude determination from accelerometer

Accelerometer output is used to obtain roll and pitch. The relational equation expressed accelerometer output equals to add acceleration of body frame and acceleration of gravity[5].

$$f^b = \dot{v}^b + \omega_{nb}^b \times v^b - g^b \approx \begin{bmatrix} g\sin\theta \\ -g\sin\phi\cos\theta \\ -g\cos\phi\cos\theta \end{bmatrix} \tag{6}$$

where f^b is specific force and g^b is the gravity vector in body frame. v is linear velocity component of each axis and it can't be measured without external sensors so that we ignore those terms. Therefore Eq. (6) is reduces to the following as :

$$\theta = \sin^{-1}\left(\frac{f_x}{g}\right), \quad \phi = \sin^{-1}\left(\frac{-f_y}{g\cos\theta}\right) \tag{7}$$

We can calculate roll and pitch using simple equation. Therefore, we can calculate roll and pitch by fusion of gyro and accelerometer.

III. KALMAN FILTER USING FUZZY LOGIC SYTEM

1. Kalman filter

Kalman filter is used for fusion of gyro and accelerometer. Kalman filter is consisted of process model and measurement model.

$$\begin{aligned} x_k &= Ax_{k-1} + Bu_k + w_{k-1} \\ z_k &= Hx_k + v_k \end{aligned} \tag{8}$$

where w_k and v_k represent the process and measurement noise respectively. We are assumed to be independent and with normal probability distributions.

$$\begin{aligned} w_k &\sim N(0,\, Q) \\ v_k &\sim N(0,\, R) \end{aligned} \tag{9}$$

where Q is the process noise covariance and R is the measurement noise covariance[6-7].

We used that process model is gyro output and measurement model is calculated attitude of accelerometer as shown in Fig. 2. However, parameter of Kalman filter can't estimate accuracy values. Through experiment, we could know that ARS has large errors when it is greatly changed so we used fuzzy logic for improving performance [8].

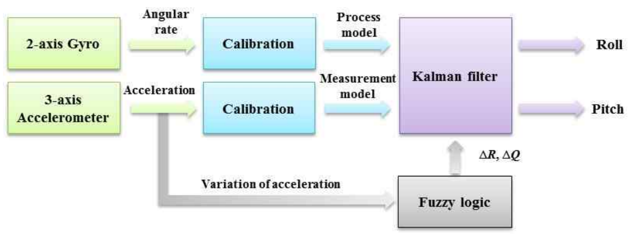

Fig.2. Structure of attitude reference system

2. Fuzzy logic for controlling parameter

We used fuzzy logic for modifying process and measurement noise covariance. Before Kalman filter is used, we have to calculate Fuzzy logic using output of sensors and reflect changed parameter. Input of fuzzy logic is acceleration's variation of x axis and y axis and output is variation of R, Q. We used mamdani method and simple rules. The following two fuzzy rules are used :

Rule1. If $|\Delta a|$ is small then R is increased and Q is decreased.

Rule2. If $|\Delta a|$ is large then R is decreased and Q is increased.

where $|\Delta a|$ is variation of each axis' accelerometer output and absolute value. If variation of acceleration is large then we can't trust output of accelerometer and R must be changed to be increased because sensor movement is supposed to be measured. The membership functions of fuzzy sets are shown in Fig. 3.

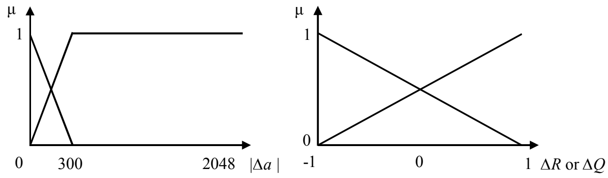

Fig.3. Membership functions

Range of Δa is determined by output range of accelerometer sensor and heuristic method. Output range of using accelerometer is from -1024 to 1024.

IV. EXPERIMENT

The proposed parameter tuning method of Kalman filter using fuzzy logic has been tested and compared with Crossbow Nav420CA. Nav420CA is INS(Inertial Navigation System). It can measure roll, pitch and has high accuracy which is 0.75°rms. We made ARS module and it consists of microprocessor, 3-axis accelerometer and 2-axis gyro. We used LIS3LV02DQ accelerometer and IDG-300 gyro. Microprocessor is used ATmega128. We measured roll and pitch of ARS module and Nav420CA at the same time using the stewart platform in shown as Fig.4.

The results obtained that proposed algorithm is better than Kalman filter in shown as Fig. 5. We confirmed response delay and it is due to response rate of microprocessor and parameter of Kalman filter. To knowing accuracy, we calculated errors based upon a simple root mean squared error (RMSE). Here, we assumed truth model is Nav420CA. When we used only Kalman filter, RMSE is in shown as Table 1. Because of reducing errors, we can tell that proposed algorithm is better than simple Kalman filter.

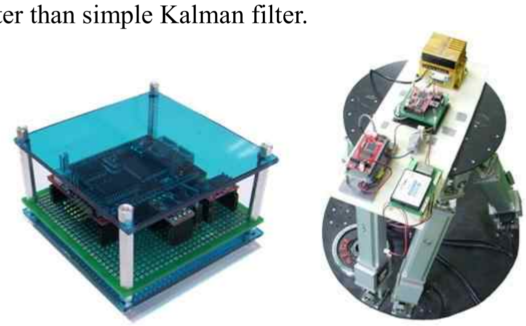

Fig.4. ARS module and experimental environment

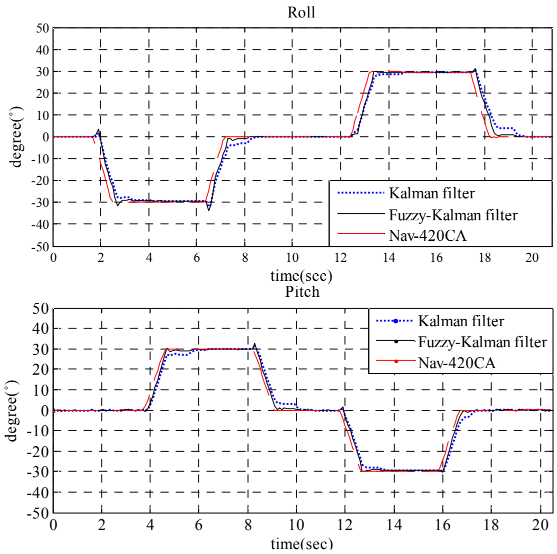

Fig.5. Roll and pitch rotation test result

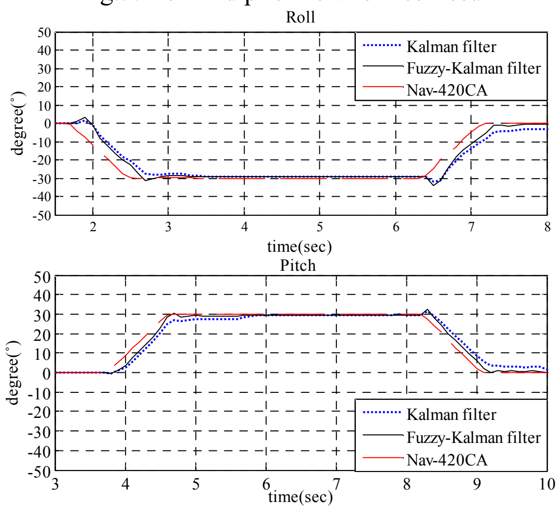

Fig.6. Zoom in roll and pitch rotation test result

Table 1. RMSE of the test result

	Kalman filter		Fuzzy-Kalman filter	
	roll	pitch	roll	pitch
Static	0.20	0.10	0.20	0.03
Dynamic	1.43	1.07	0.72	0.71

V. CONCLUSION

This paper proposed parameter of Kalman filter tuning method using fuzzy logic. In order to attitude calculation, we used gyro calibration by Euler angle method. Fusion of sensors is usually used Kalman filter. We determined process model is output of calibrated gyro and measurement model is calculated attitude of accelerometer. However, result of this algorithm has large errors when it moves greatly. To this problem, we changed parameter of Kalman filter using fuzzy logic. If

ARS module is moved large, then we trust gyro so that Q is decreased and R is increased. We tested to confirm proposed method. We made ARS module using 3-axis accelerometer and 2 axis gyro. The result is reduced errors than simple Kalman filter. We confirmed that proposed algorithm is very simple but it is high performance. If we have a chance, we want to research magnetic sensor. Magnetic sensor is used calculation of yaw. We will add our ARS module to magnetic sensor and then we will be able to make AHRS(Attitude Heading Reference System) module.

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