Experimental study on the phase delay of low-cost IMU, low pass, and Kalman filter and its effect on the phase margin of angle estimation

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ABSTRACT

Nowadays, many low-cost MEMS inertial measurement units (IMUS) or motion processing units (MPUs) can be found in the market which can be used in control system. For the sensors to be useful in control system, the phase delay and frequency response should be given because it directly affects the stability of the closed loop system. However, almost all of the makers of low-cost MEMS IMUs or MPUs do not supply the phase characteristics. Furthermore, their performance characteristics under high frequency vibration are not given, even though they are very important when the sensors are used on drones or flapping MAVs.

In this paper, we developed an external measuring device that can accurately measure the rotational angle value from the vibrating MAVs. It is composed of 1-DOF gimbal with a servo motor to produce rotation and one rotary encoder to measure the rotation. The outer frames of the gimbals are made of carbon plates. At this time, the rotation angle is limited to +/- 90 degrees. The IMU to be evaluated is attached to the gimbal and it is connected to the microprocessor. Then, the servo command, encoder angle, and IMU data, which are obtained by the microprocessor, are sent to the computer for data processing and filter simulation. The filters used are low pass filter and Kalman filter. The experiments are conducted by rotating the IMU in sinusoidal and step pattern with and without flapping motion. Accordingly, the effect of filter parameters on estimated angle, including the phase delay, can be observed and studied.

1 INTRODUCTION

Over the years, low-cost MEMS IMUs and MPUs have been available on the market [1]. They are widely used in various applications, especially in small vehicles, such as micro aerial vehicle (MAV) or micro underwater vehicle (MUV). However, it is well known that the output values of such low-cost MEMS IMUs and MPUs contain a lot of noises. To solve this problem, the output value is filtered by software through low-pass filter, Kalman filter, complementary filter, or any other filters. However, if the filter is used, a phase delay occurs between the actual value and the estimated value. The phase delay due to the filters are added to the inherent delay of the sensor. The delay is an important factor in our analysis of flight data, or in controlling drones or MAVs. Also, via the gimbal system experiment, we can check the performance of the IMU under high frequency oscillation, which is critical if an IMU or MPU to be used in vibrating environment like flapping MAVs.

In this study, we developed a 1-DOF rotation measurement system consisting of a 1-DOF gimbal with one servo motor and two encoders. The servo motor is used to drive the rotating axis of the

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gimbal and the encoders are attached to both sides of the shaft to measure the rotation angle. Later we found that one encoder is enough to get the reference angle information, and thus one encoder only is used to get the reference motion data in the experiment. Various designs of gimbal system can be found for different purposes such as controlling position of camera on MAV [2], attitude estimation and control [3], or removing bias [4]. Our design is different compared to the conventional ones in that it can mount directly the flapping MAVs and drive the gimbal with desired motion and we can get measured data from the IMU mounted on the flapping MAV as well as the reference motion data from the encoder so that we can evaluate the performance of the IMU mounted on the flapping MAV under more realistic flapping environment.

The flapping-wing MAV [5] containing the IMU is mounted on the gimbal system. The estimated angle values are obtained by calculating angle from accelerometer and applying low pass and Kalman filter using the rate information from the gyroscope in the IMU[6]. The estimated angle is compared with the reference angle data obtained from the encoder mounted on the shaft of the gimbal system.

2 Gimbal System

In this paper, we aim to develop a 1-DOF rotation measurement verification system to study the phase delay of low-cost IMU, low pass, and Kalman filter and its effect on the stability margin of feedback control system, as well as, to study the effect of vibration to the performance of small IMU

2.1 Mechanical design of the gimbal system

Figure 1 shows a 3D drawing of the target 2-DOF rotation measurement verification device to be fabricated for the future research. The currently developed 1-DOF rotation measurement verification device, which is shown in the Figure 2, consists of a gimbal, two encoders to measure the rotation angle, a supporter to support the gimbal and encoders, and a fixing device to fix the measurement object to the gimbal. Encoders were mounted on both sides of the gimbal so that the gimbals are not bent and they are being accurately measured. These encoders are used to measure the actual angle at which the gimbal is rotated.

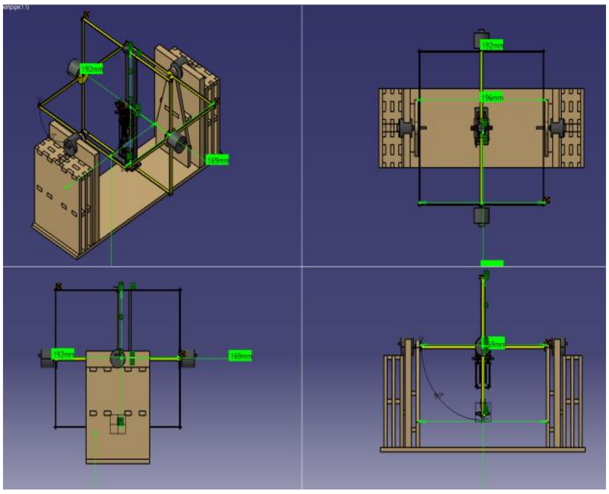


Figure 1 - Conceptual design of 2-DOF rotation measurement verification device for future research

The supporter and the fixing device were manufactured using a 5T-acrylic plate using a laser cutting machine. The gimbal was made of 1T-carbon plate using CNC.

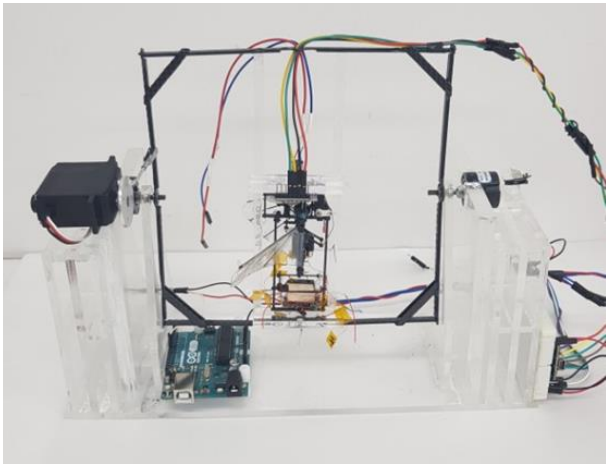


Figure 2 - 1-DOF rotation measurement verification device

2.2 Data acquisition of the 1-DOF gimbal system

Using the Mbed LPC1768, the encoder value was read through the SPI communication and transferred to the computer through another serial communication. The sampling frequency was 100Hz.

The encoder used for this device is AEAT-6012-A06, a high performance, low cost, optical absolute magnetic encoder module, designed to detect absolute reference angular position. The servo used for this device is BM-1301B. It is a digital servo made for robots. It was chosen because it has strong torque and accurate control over price.

2.3 operation test

Sine waves or square waves are generated in Arduino Uno board and the PWM signal corresponding to the motions are sent to the servo motor. A sine wave of 1Hz was generated for the operation test of the 1-DOF gimbal system. The amplitude was set as 20 degrees peak to peak.

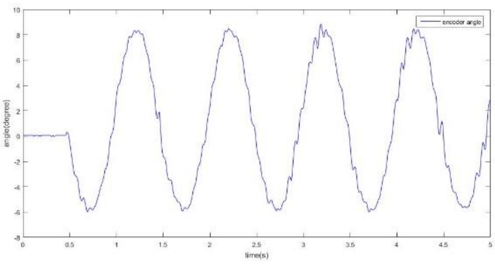


Figure 3 – result of operation test

The reference data obtained from the encoder are shown in Figure 3. The measured gimbal motion angle shows sine wave with 14 degrees peak to peak even though we applied sine wave with amplitude 20 degrees peak to peak. It is due to that the servo and the gimbal are connected through a mechanical linkage and the amplitude is scaled down due to the mechanical linkage. Thus all the data in this paper is scaled down due to the linkage effect.

3 Experiment

Currently, there are various types of inexpensive MPUs on the market. The IMU used in this experiment is MPU-9250. This sensor includes gyroscopes, accelerometer, and magnetometer. For convenience, we use sensor module and microprocessor MBED LPC1768.

3.1 Experiment configuration

Figure 4 shows a block diagram of the system for experiments. After the microprocessor MBED LPC1768 acquires data from sensor module, it processes the data and transfers it to the computer so that the data can be verified. The sampling rate of the sensors are set as 100 Hz.

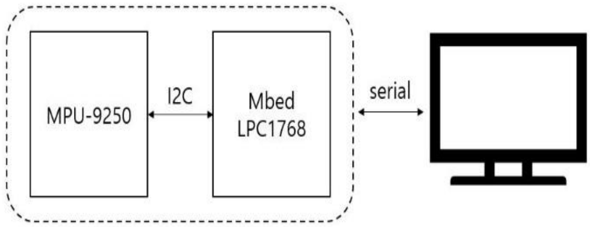


Figure 4 – IMU operation experiment block diagram

In this study, the data is filtered using a low-pass filter and a Kalman filter to obtain estimated angle. The experiment was conducted using KU-beetle of Konkuk University. We observe the phase delay phenomenon by comparing the encoder value coming out by rotating the gimbals and the value coming out through the filter by controlling the servo with Arduino Uno.

3.2 IMU data processing

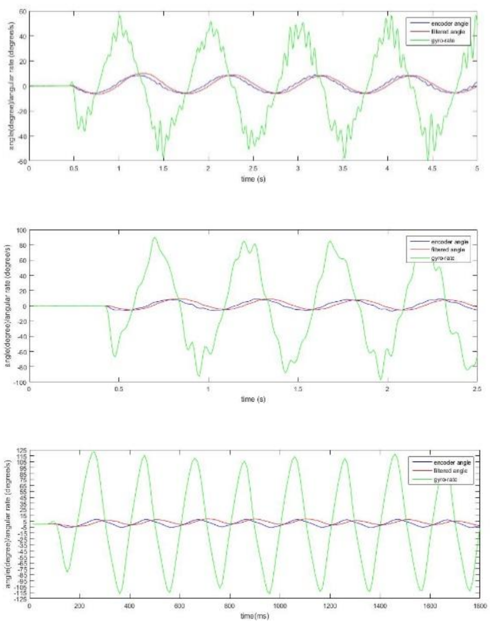
Among the data of IMU, only the gyro value of one axis and acceleration of three axes are used. The acceleration values of the three axes from the IMU are each passed through a low-pass filter. Then, the attitude angle is first extracted using the direction of the gravity acceleration measurement. The angle is calculated after a low-pass filter to move out the effect of vibration. The acceleration angle is calculated using equation:

$$\theta_{acc}[k] = \frac{360}{2\pi} tan^{-1}\left(\frac{a_x[k]}{\sqrt{a_y[k]^2+a_z[k]^2}}\right) \qquad (1)$$

The a_x, a_y, and a_z are measured and filtered acceleration signals for each axis. Then, the filtered angle was obtained by performing a Kalman filter processing on the gyro value of the single axis and the acceleration angle obtained above. The low pass and Kalman filter equation used in the simulation can be found in [4]

3.3 Experiment result

Experimental data were compared between encoder angle, filtered angle and gyro rate. In the first experiment, the amplitude of the signal sent to the servo was 20 degrees without flapping. There are four types of signals: a sine wave with periods of 1, 2, and 3 Hz and a periodic 0.5 Hz rectangular wave. The second test signal is a sine wave with an amplitude of 20 degrees and a period of 0.5 Hz. The difference from the first experiment is that FMAV flapping for a certain time.



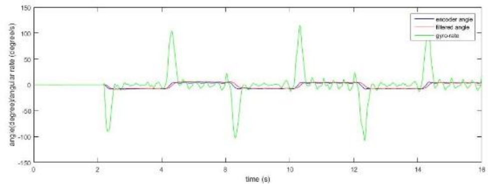


Figure 5 – non-flapping experiment

Figure 5 shows the result graph for the first experiment. From the top is a 1 Hz sine wave, a 2 Hz sine wave, a 5 Hz sine wave and a 0.5 Hz square wave. Comparing the filtered angle and the encoder angle, the phase delay of the filtered angle can be confirmed in all four graphs. This phase delay is critical especially if the closed loop is to have wide bandwidth. To overcome the phase delay of the sensing system, the closed loop controller should have enough phase margin greater than the phase delay of the sensing elment and the filtering software.

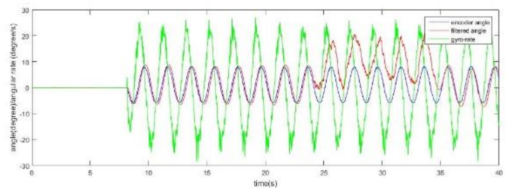


Figure 6 – flapping experiment

Figure 6 shows the result graph for the second experiment. The first 25 seconds were measured without flapping to see the obvious results. After then, 10 seconds of flapping is applied, and the flapping is stopped. It can be seen that the offset of the filtered angle increases by about 5 degrees during 10 seconds of flapping. The reason for this phenomenon is considered a result of a large vibration of the acceleration value during the flapping, and the accelerometer bias is affected by the vibration. Thus to improve the accuracy of the IMU, it is critical to use some mechanical vibration isolator to reduce the effect of mechanical vibration.

4 CONCLUSIONS

Through this study, the performance of low-cost IMU can be verified through a gimbal system, i.e., 1-DOF rotation measurement verification device. As can be seen from the experiment, the estimated value of the IMU through the filter has a phase delay phenomenon. The phase delay should be treated well to make a better closed-loop control system. Especially it is necessary for the closed loop control system to have enough phase margin to overcome the uncertainty due to the phase delay. Also the accelerometer is affected much by the high frequency vibration and it invokes offset change in the gyro-accelerometer filtering system. To reduce the error due to the offset change, it is necessary to use mechanical isolator to damp out high frequency oscillation

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