Content list available at JournalPark

Turkish Journal of Forecasting

Journal Homepage: tjforecasting.com

Orientation Determination in IMU Sensor with Complementary Filter

M.N. Oz[1,*], S. Budak[1], E. Kurnaz[1], A. Durdu[1]

[1]*Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Electrical Electronics Engineering, Konya, Turkey*

A R T I C L E   I N F O

Article history:

Received	04	June	2022
Accepted	21	June	2022
Available online	31	August	2022

Keywords:

Unmanned aerial vehicles
STM32F407VG
IMU
Complementary filter
PID

R E S E A R C H   A R T I C L E

A B S T R A C T

The use of unmanned aerial vehicles (UAV) systems has increased in recent years. Therefore, studies on UAVs have increased today. In this direction, the production of UAV systems with domestic resources has gained importance. In this study, it is desired to develop a domestic and national flight control card and software. In the flight control board designed for the UAV, it is aimed to keep the vehicle in balance in the air. Accurate measurement of platform orientation plays an important role in many applications such as aerospace, robotics, navigation, marine, machine interaction [1]. Inertial Measurement Unit (IMU) sensor was used to accurately measure the orientation of the UAV. IMU sensor is widely used in UAVs due to its light weight and low energy consumption. In this direction, the need for a filter has emerged in the IMU sensor, which is used to accurately measure the orientation of the unmanned aerial vehicle. In this study, a complementary filter was applied on the IMU sensor. Thanks to this filter, it has been observed that the accuracy of the data received from the IMU sensor has increased. Based on the data obtained, a Proportional Integral Derivative (PID) algorithm was developed, and the vehicle was kept in balance. In this study, ARMCortex-M4 based STM32F407VG microcontroller and MPU6050 as IMU sensor were used. Keil-uVision5 compiler is preferred for software. As a result, high accuracy in the orientation detection of unmanned aerial vehicles was obtained by applying a complementary filter on the IMU sensor.

1. Introduction

The IMU sensor began to be used in the fields of aviation and navigation systems in the 1930s. The IMU sensor, which was initially limited in size and cost, has emerged as a Micro Electronic Mechanical System (MEMS)-based in recent years. This IMU sensor has attracted attention with its low cost and compact structure, and its use has increased in fields such as robotics and human motion analysis [2]. The IMU sensor is used to determine the orientation of an object in terms of acceleration, angular velocity, rotation. IMU sensor consists of accelerometer and gyroscope combination. The accelerometer is used to measure the inertial acceleration while the gyroscope measures the angular rotation. Accelerometer data cannot be produced with the effect of external forces. Mark Pedley carried out studies on the mathematics of orientation with the help of a three-axis accelerometer, also made analyses on

[*]Corresponding author.
E-mail addresses: e218221001005@ktun.edu.tr (Muhammed Nazmi Öz)

https://doi.org/10.34110/forecasting.1126184

regions of instability. For example, in vibrating environments such as airplanes and cars, the accuracy of the data is very low [3]. Accelerometers can produce accurate results in the long run. Since the accelerometer data is not sufficient to obtain stable results, it is necessary to benefit from the data from the gyroscope. A gyroscope measures angular velocities in three axes and although not as sensitive to external forces as an accelerometer, gyroscopes are more stable at detecting instantaneous changes. Noise occurs in the data received in the long term. As a result, data fusion should be performed using the gyroscope and accelerometer.

When the studies in the literature are examined, Guan and Song (2018) discussed the attitude determination problem of the automatic carrier, in which measurements taken from a low-cost IMU are given. They used a combination of gyroscope and accelerometer data based on gradient descent and complementary filtering to correct for drift due to gyroscope cumulative error. In their experimental results, they showed that the low-cost system can operate in real time and produce stable behaviour [4]. Duong et al. (2018) presented a new adjustment method for the complementary filter used for attitude prediction. Conventional Complementary Filters (CCF) used for attitude estimation have fixed filter gain. In this study, Fuzzy Tuned Complementary Filter (FTCF) algorithm is proposed by changing the fixed filter gain. The proposed algorithm has been shown to significantly reduce errors in attitude prediction [5]. Gui et al. (2015) investigate real-time bending measurement using IMU in their work. It presents a study on the complement and Kalman filter for slope measurement. In the study, both static and dynamic experiments were carried out. In the experiments, it was found that the complementary filter greatly reduces the workload as it requires less computation and only one filter coefficient needs to be adjusted. Both the complementary filter and the Kalman filter were able to obtain smooth and accurate results in static or dynamic tests. Considering the fine-tuned filter coefficients, it has been observed that the result of the complementary filter can be more stable and accurate than the Kalman filter. However, both techniques can be used effectively in slope detection if appropriate filter parameters are available [6]. The data fusion process is important to calculate a reliable orientation for real-time applications. IMU data fusion process is done with various mathematical formulas. According to the literature research, the constant gain of the complementary filter algorithm limits the orientation estimation of the system for varying motion states. Therefore, the fuzzy logic algorithm is used together with the complementary filter to find the appropriate gain value according to the motion of the system. This coefficient is used to change the cut off frequency of the complementary filter. This coefficient, which takes different values according to the stationary and mobile nature of the system, will increase the accuracy of the angle information desired to be obtained by changing the weights of the low and high pass filters on the system. The purpose of the fuzzy logic-based complementary filter is to make the cut-off frequency value of the complementary filter with a fixed cut-off frequency dynamic [7].

Sensor fusion is the process of obtaining information with the least error by combining data from different sensors such as gyroscope and accelerometer [8]. The most widely used data fusion algorithms have been identified as the Kalman filter and the complementary filter. Both filters have advantages and disadvantages. The Kalman filter is difficult to implement and understand. For this reason, it has been decided to use a complementary filter as an easier and more understandable algorithm. In this study, sensor fusion was performed using a complementary filter.

2. Material and Methods

In this section, the method of applying the complementary filter used for IMU data fusion will be discussed. In this study, ARM-Cortex M4 based STM32F407VG microcontroller was used. Although it has an 8 MHz crystal, its operating frequency can rise to 168 MHz. It contains 1 MB of flash memory and 192 KB of RAM.

2.1. Inertial measurement unit (IMU)

In this study, the MPU6050 IMU sensor was preferred. This sensor has 6 degrees of freedom. It consists of a three-axis gyroscope and a three-axis accelerometer. It communicates with I2C communication protocol. The image of the IMU sensor used in the project is given in Figure 1.

Figure 1. MPU6050 IMU sensor

2.2. Complementary filter

The complementary filter was introduced by Shane Colton in 2007 [9]. The complementary filter algorithm consists of a low-pass filter and a high-pass filter. These filter outputs are then combined. In this way, a more reliable orientation estimation is made by eliminating the deviation error and noise error in long-term applications. A complementary filter should be used to blend different sensors and obtain a good measurement. A good measurement here is a noise-free signal that is close to the correct value. However, the complementary filter can only be used for sensors with complementary frequency characteristics.

In this study, it was used to accurately determine the orientation of the unmanned aerial vehicle. Gyroscope data is used for instantaneous changes. The gyroscope gives more accurate data in instantaneous changes and is not affected by external forces. The gyroscope works well at high frequency, correcting the accelerometer error, but causing an ever-increasing bias error at low frequency. Accelerometers work correctly at low frequency. In sudden changes, noise occurs at the output of the accelerometer. The low-pass filter applied to the accelerometer allows long-term changes and prevents short-term fluctuations. A high-pass filter is applied to the data received from the gyroscope. With the high-pass filter, short-term signals are allowed, and long-term fluctuations are prevented. The most important factor that negatively affects the accuracy of the data taken from the gyroscope is the slip rate. Slippages are prevented with a high-pass filter. The working principle of the complementary filter is given in Figure 2. A complementary filter is a simple and common way of combining sensor data. Complementary features of the sensors are used in the algorithm used to overcome the weaknesses of the other sensor by using the advantageous aspects of one sensor.

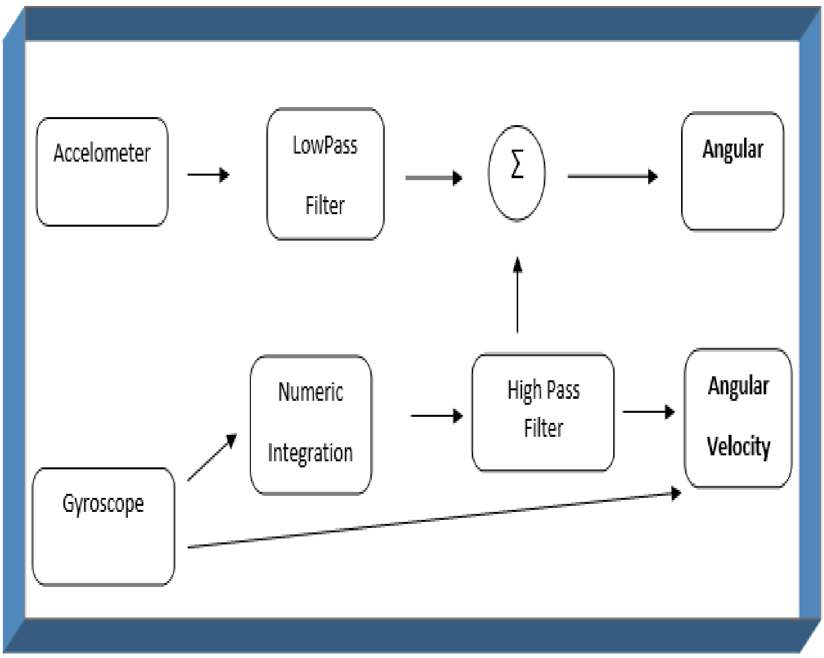

Figure 2. Working principle of the complementary filter

Complementary filter is mathematically expressed by Equation 1 and Equation 2 below.

$$\theta_{angle} = \alpha * (GyroscopeData) + (1 - \alpha) * AccelerometerData \quad (1)$$

$$\theta_{angle} = \alpha * \left(\theta_{angle} + \omega_{gyro} * dt\right) + (1 - \alpha) * accData \quad (2)$$

'θ_{angle}' is the filtered angle value. 'ω_{gyro}' is the angular velocity value taken from the gyroscope. 'α' is the filter coefficient. 'accData' refers to the data received from the accelerometer. If the desired time constant and sampling rate are known, the 'α' value of the filter coefficient can be obtained. To determine the 'α' value, the mathematical formula given in Equation 3 should be used.

$$\tau = \frac{\alpha * dt}{1-\alpha} \qquad \alpha = \frac{\tau}{\tau + dt} \quad (3)$$

where 'τ' is the time constant.

2.3. Sensor fusion

The fact that the sensors have advantages or disadvantages relative to each other makes it necessary to use them together. More positive results can be obtained when the data provided by more than one sensor is combined and used. Errors due to combined sensor data may be less than sensor errors evaluated separately. By combining the sensors, more stable and complementary sensor structures can be created. In addition, if one of the sensors fails or cannot work correctly, it affects the operation of the system less thanks to the data received from other sensors.

In this study, noise errors occur especially in vibration situations and oscillation movements. Systematic errors increase over time, and this is manifested as an angular shift. To eliminate these effects, the method of combining data from two sensors is used. Due to sensor errors and noise, distorted data is obtained. The real result is tried to be reached by considering the instantaneous data, the estimated previous data, and the noise assumptions. It is easy to implement on microcontrollers as it contains less processing intensity than similar methods.

3. Results

Accidents may occur in the balanced positioning of UAVs. To reduce these accidents, code trials were conducted in an experimental setup. The experimental setup used in the study is given in Figure 3. A stable and more reliable test setup is designed. The visual of the design is given in Figure 4. In this study, STM32F407 microcontroller was used, and complementary filter was applied on the IMU sensor. STM Studio program was used to examine the filtered angle values in more detail. In Figure 5, accelerometer, gyroscope and filtered angle values are compared. Accordingly, it has been observed that while the gyroscope produces data with high accuracy in instantaneous changes, the accelerometer produces more accurate data at low frequencies. It has been observed that the gyroscopes have increased bias error at low frequencies. By applying a complementary filter, the advantages of both sensors have been utilized and more accurate data has been obtained.

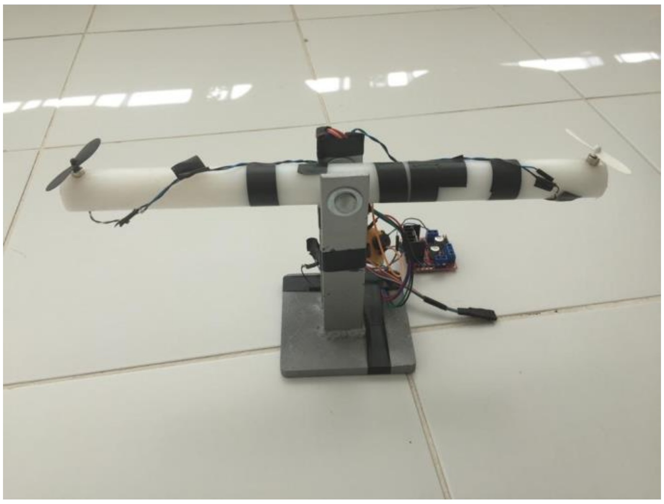

Figure 3. Experiment mechanism

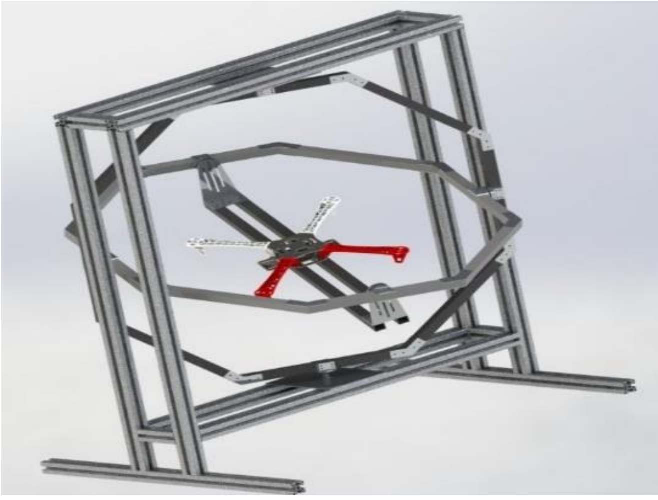

Figure 4. Designed experiment mechanism

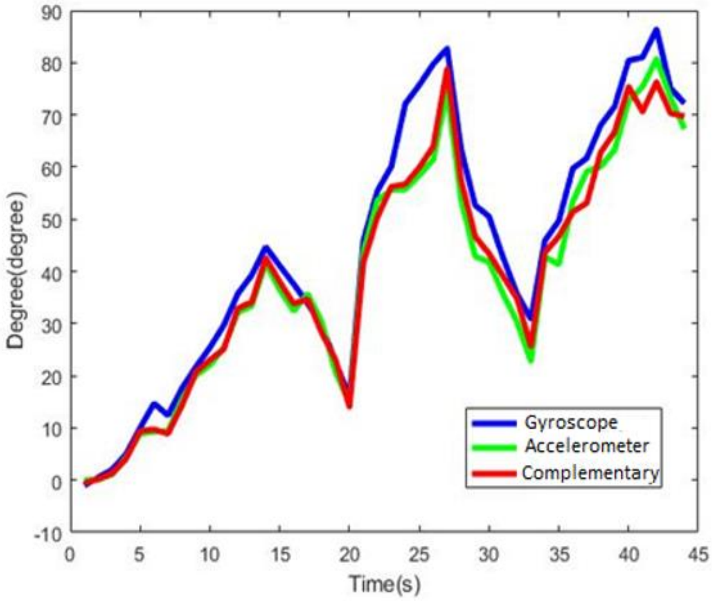

Figure 5. Comparison of accelerometer, gyroscope, complementary filter data

4. Conclusion

To keep the unmanned aerial vehicle in balance, a supplemental filter has been applied on the IMU sensor. With the data obtained because of this filter, the PID algorithm has been developed and the vehicle has been kept in balance. Equilibrium could not be achieved in the experiments without filter application. Thanks to the filter, the angle values obtained from the sensor have become stable and reliable. Therefore, the application of the filter is of great importance. Filtered angle values were examined by the STM Studio program. Code trials were carried out thanks to the balance platform. To obtain safe and accurate results, a more functional experimental setup should be produced.

References

[1] S. O. Madgwick, A. J. Harrison, R. Vaidyanathan. "Estimation of IMU and MARG orientation using a gradient descent algorithm." *2011 IEEE international conference on rehabilitation robotics*. IEEE, 2011.

[2] N. Ahmad, R. A. R. Ghazilla, N. M. Khairi & V. Kasi, (2013). Reviews on various inertial measurement unit (IMU) sensor applications. *International Journal of Signal Processing Systems*, *1*(2), 256-262.

[3] M. Pedley, (2013). Tilt sensing using a three-axis accelerometer. *Freescale semiconductor application note*, *1*, 2012-2013.

[4] Y. Guan, & X. Song, (2018). Sensor fusion of gyroscope and accelerometer for low-cost attitude determination system. In *2018 Chinese Automation Congress (CAC)* (pp. 1068-1072). IEEE.

[5] D. Q. Duong, J. Sun, T. P. Nguyen, & L. Luo, (2016, August). Attitude estimation by using MEMS IMU with fuzzy tuned complementary filter. In *2016 IEEE International Conference on Electronic Information and Communication Technology (ICEICT)* (pp. 372-378). IEEE.

[6] P. Gui, L. Tang, & S. Mukhopadhyay, (2015, June). MEMS based IMU for tilting measurement: Comparison of complementary and kalman filter based data fusion. In *2015 IEEE 10th conference on Industrial Electronics and Applications (ICIEA)* (pp. 2004-2009). IEEE.

[7] X. Shen, M. Yao, W. Jia, & D. Yuan, (2012). Adaptive complementary filter using fuzzy logic and simultaneous perturbation stochastic approximation algorithm. *Measurement*, *45*(5), 1257-1265.

[8] W. Elmenreich, (2002). *Sensor fusion in time-triggered systems* (Doctoral dissertation).

[9] S. Colton, & F. R. C. Mentor, (2007). The balance filter. *Presentation, Massachusetts Institute of Technology*.