An Optimized Complementary Filter For An Inertial Measurement Unit Contain MPU6050 Sensor

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Abstract *(It can be said that the system of sensing the tilt angle and speed of a multi-rotor copter come in the first rank among all the other sensors on the multi-rotor copters and all other planes due to its important roles for stabilization. The MPU6050 sensor is one of the most popular sensors in this field. It has an embedded 3-axis accelerometer and a 3-axis gyroscope. It is a simple sensor in dealing with it and extracting accurate data. Everything changes when this sensor is placed on the plane. It becomes very complicated to deal with it due to vibration of the motors on the multirotor copter. In this study, two main problems were diagnosed was solved that appear in most sensors when they are applied to a high-frequency vibrating environment. The first problem is how to get a precise angle of the sensor despite the presence of vibration. The second problem is how to overcome the errors that appear when the multirotor copter revolves around its vertical axis during the tilting in either direction x or y or both. The first problem was solved in two steps. The first step involves mixing data of the gyroscope sensor with the data of auxetometer sensor by a mathematical equation based on optimized complementary filter using gray wolf optimization algorithm GWO. The second step involves designing a suitable FIR filter for data. The second problem was solved by finding a non-linear mathematical relationship between the angles of the copter in both X and Y directions, and the rotation around the vertical axis of multirotor copter frame.*

***Index Terms*— MPU6050, Complementary Filter, GW, yaw-tilting problem.**

I. INTRODUCTION

The MPU6050 devices combine a 3-axis accelerometer and a 3-axis gyroscope on the same board together with an onboard Digital Motion Processor capable of processing complex 9-axis Motion Fusion algorithms. Multirotor copter is flying robot has six degrees of freedom. It uses the rotors to generate the required thrust to fly. The flight controller has the responsibility of controlling the tilting angle and orientation based on the data received from the sensors on the copter. There are multiple sensors on the copter like gyroscope, accelerometer, GPS, and compass. The output of the flight control unit controls the speed of each motor in order to achieve the requirements like stabilization or track a path. Each motor spin in different direction comparing with neighbor motors in order to balance the torques on their associated axes. Therefore, there is no need for the tail rotor[1].

Multirotor copter depends on robust control algorithms to achieve its mission. But, the classical design and Preparation process with its multiple stages; resources, efforts and a long cycle of time are exhausted. The simulation process is also another drawback where the simulation period is too long especially for complex systems that have multi parameters. the presented paper proposes an effective method for evaluating and testing any Unmanned Aerial Vehicles UAV flight control system, through building up a 6DoF indoor flight environment for real-time simulation, based on MATLAB-Simulink/FPGA Hardware-In-the Loop simulation (HIL). Attitude the estimation algorithm based on direction cosine matrix (DCM) is developed to demonstrate the effectiveness of the proposed testbed [2].

Ultra-wideband UWB wireless localization systems for highly precise applications. The problem addressed in the presented paper is enabling novel applications with autonomous UAV systems. The proposed system consists of Accelerometer, Gyroscope (MPU-6050), Optical-flow sensor, Magnetometer, Ultrasound sensor, Pressure sensor, and GNSS receiver. The authors made experiments of simultaneous flight of three UAVs [3].

This study focus on the attitude estimation of the multi-rotor copter. It is difficult to obtain accurate attitude values due to the nonlinearity of this system as well as strong coupling. Complementary filter algorithm is applied is used to solve this problem. The Inertial Measurement Unit (IMU) is used to estimate four-rotor helicopters attitudes using MPU-6050[4].

The paper proposes a simple open unmanned aerial vehicle platform. It's based on open-source flight controller used MPU6050 as a gyroscope and accelerometer. Experiments of the proposed system show that the multi-rotor copter can effectively control its flight [5].

Kalman filter is used in this paper to estimate the values of the data received from inertial measurement unit IMU and sensors like pressure sensor and MPU6050. this estimator provides smooth data for the flight controller which increase the stability of the copter as well as other features like hold altitude or auto-landing [6].

This paper presents the proposal of an aerial photography system depending on open-source flight controller. Each part used in this system is an open-source like ground station, flight controller, camera controller software, and system design. The experimental result shows that the low-cost UAV is capable for photography applications. MPU6000/6050 used in the open-source flight controller system [7].

Twin rotor control system is proposed in this paper using State Feedback and Fuzzy Controllers. They achieve a fast rise time and a little overshoot. MPU6050 used in the system to sense the angular velocity. Experiments show that fuzzy controller has a slower response than others (PID and State Feedback) controllers [8].

In this paper, MPU6050 used for stabilization purpose of the quadcopter. Some experiments results show the proposed system is small size, lightweight, low power consumption [9].

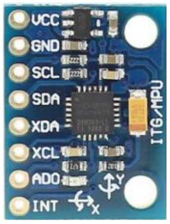

Fig.1 MPU 6050

II. Problem Description

In this research, two major problems are presented on the aircraft using the MPU6050 shown in Fig. 1 or other versions as a tilting measurements sensor.

In order to accurately describe the problem, first some facts about the sensor will be explained.

The output of this sensor, in fact, is used to calculate the acceleration in the three main axes X, Y, and Z as well as the rotational velocities around the same axes. For precise control of the multi-rotor copter. The control system needs a value of tilting, not the rotational speed. This can be calculated by integrating on the angular velocity to obtain the angle around the three directions.

Everything seems to be good, but there is a constant fact that all sensors contain an error, although it is very little, the error exists. This error in measuring of the speed leads to an error in the calculation of the angle resulting a cumulative error as shown in Fig 2 because the present angle depends on the previous angle as a starting point. This cumulative error leads to major errors over time as shown in Fig 3 and thus the plane becomes unstable

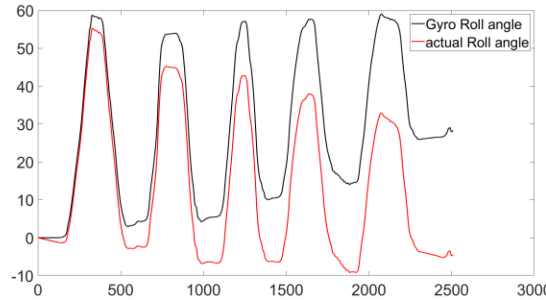

Fig. 2 real and measured roll angle out of Gyro

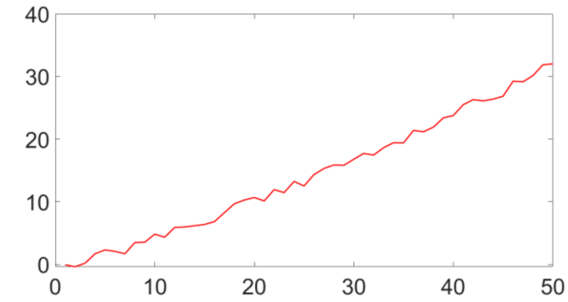

Fig. 3 Gyro error signal

There is another way to know the tilt angle of the plane around three axes using the built-in accelerometer in the MPU 6050. This technique measures the angle directly without the need for a process of integration. This technique solves the problem of cumulative errors. Another problem appears with accelerometer. It is very sensitive to vibration and therefore the data produced by it becomes meaningless in the case of a rapid vibration as vibration caused by motors in the aircraft as shown in Fig 4.

Now, the other problem that need to solve will be demonstrated. If the nose of the gyro (multi-rotor copter) is pitched up for 45 degrees for example as shown in Fig 5(b), the pitch angle is increased as it should be. Now imagine what happens when yaw of the multi-copter rotate ninety-degree clockwise as shown in Fig 5(c). The actual pitch axis of the multi-copter is now horizontal and the roll angle has increased. The pitch and roll angles measured by gyro stay exactly the same (not changed as it should be) because there is no angular motion in the pitch or roll direction.

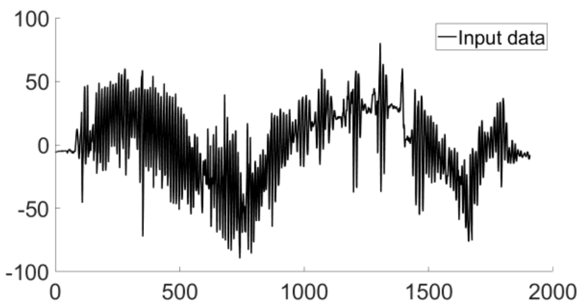

Fig. 4 roll angle calculated from Accelerometer sensor

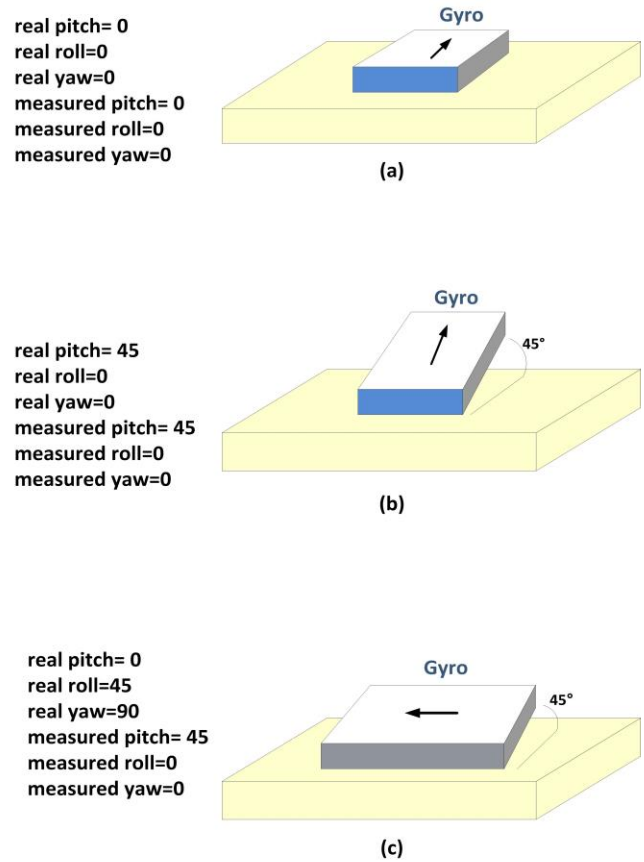

Fig. 5 Gyro yaw problem during tilt

III. PROPOSED SOLUTIONS

Problems that appear when the MPU sensor used in the multi-rotor copter is described. In this section, the proposed solutions to the mentioned problems will be discussed.

The first problem was solved by using the complementary filter as shown in Fig 5. A simple collection process was used between the data produced by the gyroscope and the resulting data from the accelerometer at different rates as shown in Fig. 6.

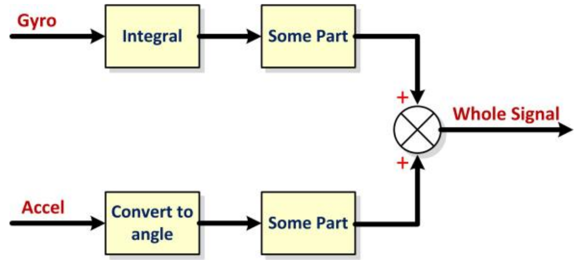

Fig. 6 Simple design of the complementary filter

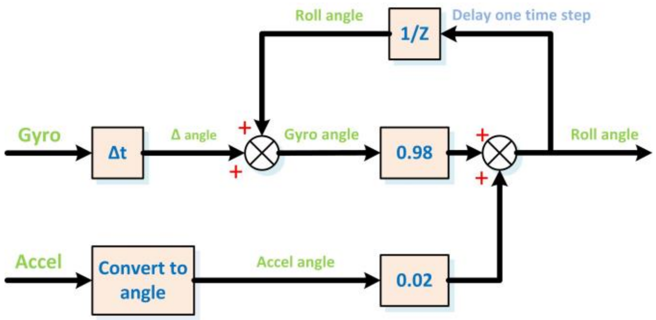

Fig. 7 The Complementry filter used in this work

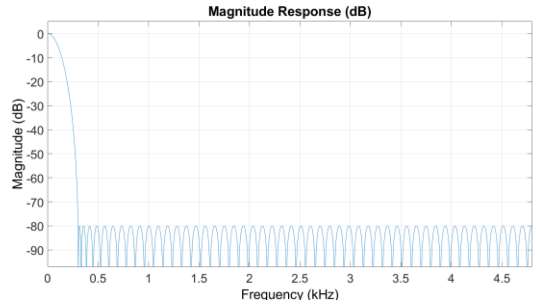

Fig. 9 Magnitude response of FIR filter

The large percentage of the data is produced by the gyroscope, while the small percentage is for the accelerometer data. Since the data of the gyroscope contains a cumulative error, a small percentage of the accelerometer data eliminating that cumulative error. On the other hand, the vibration that affects the accelerometer when it works alone, the effect is very little now because of its very low percentage, which almost does not affect the final tilting angle. A Gray Wolf Optimization GWO algorithm used to determine the ratio of each part based on the objective function. The objective function consists of two sub-objective functions which are: phase shift delay and noise produced by accelerometer as shown in equation one. The output roll angle of complementary filter shown in Fig 7. There is a very small shift delay in the signal. This signal is better than other signal received from each of them alone (gyro or accelerometer)

*Obj= k*average phase shift delay + (1-k)*ripple* *(1)*

Where
Obj: objective function
K: a constant that specifies the effect of phase shift delay
Ripple: ripple factor occurs on the output

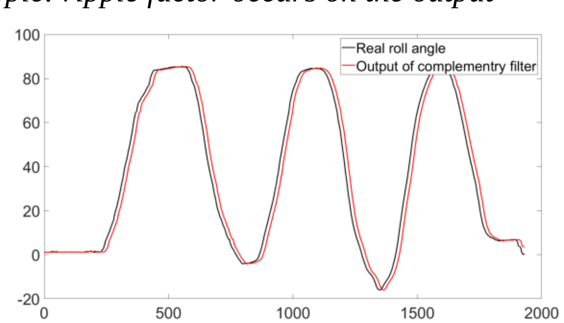

Fig. 8 real and measured roll angle out of optimized Complementry filter

The second problem of the data produced by the accelerometer was solved by designing an FIR filter for the data produced by the accelerometer sensor and thus eliminating a large percentage of the noise resulting from the vibration. The filter made the data of sensor is usable and applicable for the multi-rotor copter. Fig. 8 show the magnitude response of the low pass FIR filter designed for this paper. The suitable order is 100, cut off frequency is 2 HZ. The roll angle or data frequency is always less than 2 HZ. The output of the filter shown in figure 9.

The solution of the second problem described in the previous section is by coupling Yaw axis with pitch and roll axis. So when the Yaw axis senses a rotation, the roll angle is transferred to the pitch angle and vice versa, but what is the mathematical formula for doing this? the relationship is not linear based on some measurements. To get an idea of the change in pitch angle versus the Yaw rotation, the plot in Fig 10 is made for every five-degree of yaw movement. Now, it is easy to recognize that the shape is close to the sine function. So the function for transferring the pitch and roll angles is a sine function according to the equations 2.

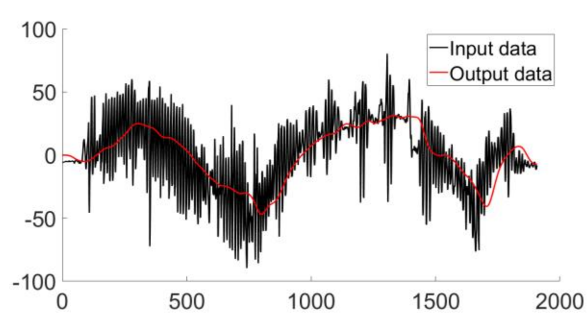

Fig. 10 Input and output of FIR filter

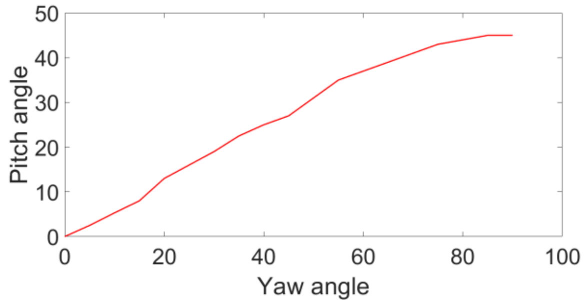

Fig. 11 pitch angle versus the Yaw rotation

*Roll angle = roll angle – pitch angle * sin (yaw angle)*
*Pitch angle = Pitch angle + roll angle * sin (yaw angle* (2)

IV. Complementary filter

At first, let's discuss the complementary filter in this work. It is a practical filter used when there is more than one sensor measure same physical value. To understand how the complementary filter works easily. First, set up a problem. Let's imagen there is a drone and try to estimate the roll angle using onboard Inertial measurement unit (IMU). The IMU has both a gyro that senses angular rate and an Accelerometer that senses linear acceleration. So the question is, how to measure the roll angle with the IMU?

Neither of these sensors can measure the roll angle directly. However, either of them can be used to estimate the roll angle.

Let's look at how to do that using just a gyro measurement.

If the Roll angle assumed to be zero degrees when the drone is sitting on the grounds, then after it takes off, the measure roll rates can used to calculate how the roll angle change over time. Now, it is possible to determine how far the drone has rotated in one-time step and then add that value to the currently estimated roll angle.

There is no important additional computational cost. Practically it is just a simple equation added to the code of the system. On the other hand. The equation was tested on a drones system. No delays or malfunctions were observed. The slight delay shown in Figure 8 does not really affect the overall system performance. For more accuracy. When using a 16 MHz processor, additional commands take about 130 microseconds. This is a very short time that can be easily exceeded by calculations.

For example, if the gyro was read ten times per second (10 HZ). The step time is 0.1 sec. the change of roll angle is multiplication of step time and the rate of change of roll angle that gets from the gyro. The new estimated roll value is summing of previous roll value with the change of roll angle. Basically, integrate the angular rate to get angles. This type of approach is called dead reckoning, it is very good for keeping track of motion over short period of time, But how it short? It depends on the noise and error characteristics of the gyro. When integrate the rate measurements in the uncorrected basis of the gyro or even just random high-frequency noise. This lead to an accumulative error that makes large difference between roll angle and the estimated roll angle. Dead reckoning is a relative measurement and there is no absolute measurement that will correct the roll over time!

Now, let's look at how to estimate the roll angle using the accelerometer.

Gravity is always pointing down. Let's imagine the drone is sitting stationary on the ground and science there are no other accelerations acting on the drone. The accelerometer will only be measuring the acceleration to the gravity. Now, the drone knows which direction is down and knowing down relative to the drone reference frame, it can determine the roll angle. A simple way to do this is just to take all tensions of the acceleration in the Y and Z directions to get angle. However, these measurements are not very precise in the short term because the accelerometer is also noisy. Even rolling the drone induce linear acceleration, if the IMU isn't located precisely at the center of rotation. For these reasons, it's hard to release only on the accelerometer for short duration very quick roll measurement but it is very stable long term because the gravity vector doesn't change over time. The measurement of gravity vector isn't wandering off like the rate based roll angle dead.

So, there are two different ways to determining the roll angle, integrating the gyro is more accurate over a short term and measuring the acceleration which is more accurate over the long term.

Now let's demonstrate what complementary do is when it runs. Complementary in the sense means combine two measurements in a way that complete each other or in other words, take some part of one measurement and added to the complementary part of the other, the sum the two parts is still one whole measurement.

In this case, keep the short term is wanted to get the benefit of the gyro and add them to the long term benefit of the accelerometer. Making these two-part complementary is easy. If the accelerometer measurement passed through low pass filter Gl(z) then the filter that pass the gyro measurement is high pass filter Gh(z) as equation 3. Since adding these two filters together equal one (they complement each other). Frequency response of the complimentary filter shown in figure 12.

*Roll angle = Gl(z) * Roll angle of accel. + Gh(z) * Roll angle of Gyro …………………(3)*

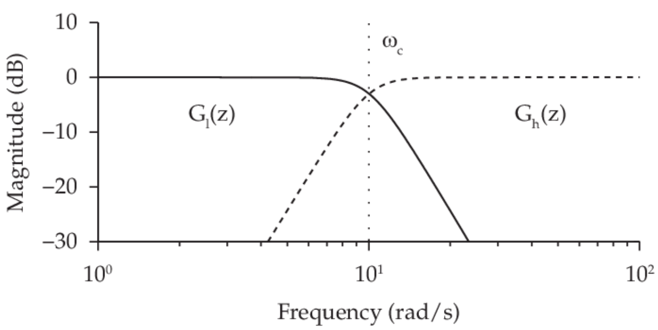

Figure 12 frequency response of the complimentary filter [10]

V. CONCLUSIONS

While working on this important sensor that plays important role in many applications, some important conclusions have been reached.

The data produced by the gyroscope sensor is the angular velocity. If the application needs to calculate a tilt angle, it will result in a cumulative error that is difficult to overcome even by using the filters.

The angle calculated from the accelerometer data is very useful when the system does not contain a vibration.

The angle calculated from the accelerometer data is not useful at all when there is vibration.

The cumulative error in the gyroscope can be overcome by using the complementary filter. Where the ratio of the accelerometer is very small.

The FIR filter or extended Kalman filter can be used to overcome the vibration effect and obtain useful data from the accelerometer.

There is a simple offset occurs on the data received by an accelerometer that must be calculated and removed.

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