Low Cost MEMS Gyroscope and Accelerometer Implementation Without Kalman Filter For Angle Estimation

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***Abstract*— These days, the accuracy of the measured tilt angle is extremely important and it is always a challenge especially for robotics application. MEMS (micro-electro-mechanical system) gyroscope and accelerometer has been widely used to measure the tilt angle along the axis. However, various studies highlighted that MEMS gyroscope and accelerometer has weakness to gain accuracy of orientation. In order to cater the low accuracy, data from the MEMS gyroscope and accelerometer require a filter where the data from both sensors will be combined by using the complementary filter. Thus, digital complementary filter is developed in such a way that the strength of one sensor will be used to overcome the weaknesses of the other sensor which is complementary to each other. The filtering will be demonstrated using MEMS gyroscope and accelerometer in different position throughout the measurement for analysis and angle estimation via complementary filter. From the simulation result, it is evident that the complementary filter method is achieved with responsive and accurate angle of 0 to 90 degrees with same as actual position at factor value of 0.97. In addition, it is not sensitive to horizontal accelerations or to gyroscope drift with microcontroller-friendly filtering system.**

I. INTRODUCTION

Gyroscope and accelerometer has been widely used to measure the tilt angle along the axis. Both are recognized in recent years, especially in telecommunication systems due to its advantages of low-cost inertial systems, miniature size, low power consumption and often aimed to be capable to measure angle [1][2][3]. Specifically, gyroscope and accelerometer are very useful in applications to unmanned aerial vehicles, automobiles, and mobile robots [4][5][6].

Gyroscopes generally used to measure the angular rate of rotation [7][8][9] where the gyroscope will provides the rate of change in orientation angle over time (angular velocity) with measurement unit degree per second. The angular rate signal must be integrated with respect to time to obtain readable angle the angular position [10][11]. Process of integration angular rate over time will create drifts [12]. These issue occurred due to the integration over time when the reading did not return to zero value [13][14][15][16]. This view is supported by [17][18][19] and in addition, the error not only affected by time but temperature and random drift.

Accelerometers are designed to measure acceleration forces where it can be determined by the measurement of the direction of the gravity force. To date, various studies in accelerometers related which focus more towards biomedical field [20][21][22][23] yet minor research working with only accelerometers specifically for angle estimation [24].

According [25], in order to measure the absolute angle definitely crucial if translation forces are included in the output signal of accelerometers. Accelerometer has a good accuracy at low frequencies and study shows that accelerometer can to sense both static and dynamic acceleration at any given time. But, it has the lacking where mainly affected by vibration stress including very sensitive to acceleration forces due to movement. The vibration will lead the accelerometer against distort and caused the signal in drift of scale factor and bias value [26].

Typical practice to obtain the angle is by double integrate the measured angular acceleration. However, [27][28] points out that the double integration produced drift. References [29][30] suggested a preventive method of adding Kalman filter to the integration procedure which more effective to reduce drift.

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In contrast to [29][30], [31][32] argues that the mathematical algorithm of Kalman Filter is too complex where it has long computational time and hard to programmed on certain 8-bit microcontroller. In addition, this view is supported by [32] and suggested that the angle estimation actually can be achieved using fewer sensors and much simpler algorithms.

Hence, building above statement, the purpose of the project is to achieve high accuracy of estimating the positioning angle by implementing digital complementary filter. The advantageous is proven with less complex of algorithm, fast estimates of angle, manage to fix noise, drift, and horizontal acceleration dependency including less CPU intensive [33][34].

The developed system consists of microcontroller, rotator, MEMS gyroscope and accelerometer. Raw data obtained from accelerometer will act as an input to the microcontroller. Both raw data will be converted into usable values (angles) before merged into digital complementary filter. Complementary filter is combination of high pass and low pass filter. . Function of complementary filter in this project is to use the strength of one sensor to overcome the weaknesses of the other sensor. Meaning that, the low pass filter will filters out the fluctuations of accelerometer while the high pass filter will reduce the effect of drift on the gyroscope concurrently [35]. Thus, the filtered output data is expected to get a smooth signal for angle estimation.

II. MATERIALS AND METHODS

This paper highlight the development of a digital complementary filter assisted using MEMS gyroscope and accelerometer to obtain accurate angle. In this experiment, a combined 3-axis gyroscope and 3-axis accelerometer sensor on the same chip. The gyroscope provide signal in terms of rotational velocity (rotation distance over time) while the accelerometer produces signal in distance over time.

The 3.3V of power supply is applied to generate the MEMS gyroscope and accelerometer to measure the angular rate of rotation and acceleration force signal. The accelerometer will be activated with 5V of power supply and communicates through the I2C protocol.

A rotator circuit is developed in order to position the accelerometer sensor in different orientation throughout the measurement. The accelerometer is placed on the horizontal rotating motor via driver to control the rotation and to switch between different positions. During the experiment, the temperature effects were put under control by keeping the unit of accelerometer at ambient temperature and the sensor will be warmed up prior to the experiments.

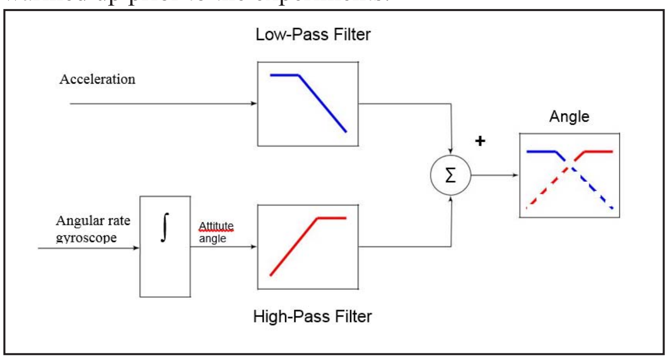

Fig. 1. Block diagram of digital complementary filter system for MEMS gyroscope and accelerometer.

Various study highlighted that the gyroscope suffers with drift and in a few time the values returned are completely wrong while the accelerometer returned a true value when the acceleration is ongoing, however accelerometer also returning values of the angle wrong due to vibrations. Hence, digital complementary filter as shown in Figure 1 was developed to cater the issues where it combines the best attributes of the gyroscope and accelerometer.

Digital complementary filter is implemented in such a way that the strength of one sensor will be used to overcome the weaknesses of the other sensor which is complementary to each other. Block diagram in Figure 1 illustrated two inputs; the accelerometer angle estimation and the gyroscope angular rate. The low pass filter will filter the high frequency signals when the accelerometer sense condition of vibration. The input of gyroscope angular rate will be integrated to emerge an attitude angle before it feed into high pass filter to negate the effect of drift. Both high-pass and low-pass filters work simultaneously, and then both signals are summed together.

The programming code in Figure 2 will read the raw X, Y & Z accelerometer values, the parameter in each call is the register within the sensor that holds the data. The sensor has a number of registers which have different functionality as documented in this datasheet. The registers for the accelerometer data are 0x3B, 0x3D, 0x3F and these hold the raw data in 16 bit two's complement format. Once the raw data is collected, it will need to be scaled and then convert it into an angle where data sheet shows that values of 16384 needs to apply to the raw accelerometer. Therefore, the collected raw data is divided with 16384 values. In a similar manner raw data from the Gyroscope is sense in the following code of Figure 3.

```
GyX=Wire.read()<<8|Wire.read();
GyY=Wire.read()<<8|Wire.read();
GyZ=Wire.read()<<8|Wire.read();
```

Fig. 2. Programming code to read gyroscope values.

```
AcX=Wire.read()<<8|Wire.read();
AcY=Wire.read()<<8|Wire.read();
AcZ=Wire.read()<<8|Wire.read();
```

Fig. 3. Programming code to read accelerometer values.

From the datasheet, the registers values 0x43, 0x45 & 0x47, hold the raw gyro data where the gyroscope outputs is in angular velocities. In order to convert the velocities from the raw data to degree/second, it will be divided by 131 values as shown in Figure 4. When both gyroscope and accelerometer data is scaled, it will then adjusted by the offset, followed by feed into the complementary filter.

```
double gyroXrate = GyX/131.0;
double gyroYrate = GyY/131.0;
```

Fig. 4. Programming code to convert the velocities data into deg per second rotation.

```
compAngle_X = 0.99 * (compAngle_X + gyroXrate * dt) + 0.01 * roll;
compAngle_Y = 0.99 * (compAngle_Y + gyroYrate * dt) + 0.01 * pitch;
```

Fig. 5. Programming code for complementary filter.

The gyroscope data is constantly integrated for each time step with the current position. The constant value of o.99 and

0.01 as shown in Figure 5 will need to total up to 1 and the both constant value will be tuned throughout the whole experiment in order to obtain the suitable value. The constant value, a of the filter always add to one, so that the produced output is accurate and linear estimate. Mathematical relation of complementary filter as shown in (1).

$$Angle = a \times (angle + gyro \times dt) + (a - 1) \times (accelerometer) \quad (1)$$

III. Results and Discussions

The signal conditioning measured from the gyroscope and accelerometer is connected to the input device via I2C communication medium. The measurement graph is captured by importing data from Parallax Data Acquisition tool (PLX-DAQ) software. Figure 6 shows the plotted graph of raw data from the accelerometer and gyroscope. Accelerometer measures inertial force while gyroscope measures angular velocities, the raw data then emerged and scaled into an angle before filtering, the output presented in Figure 7.

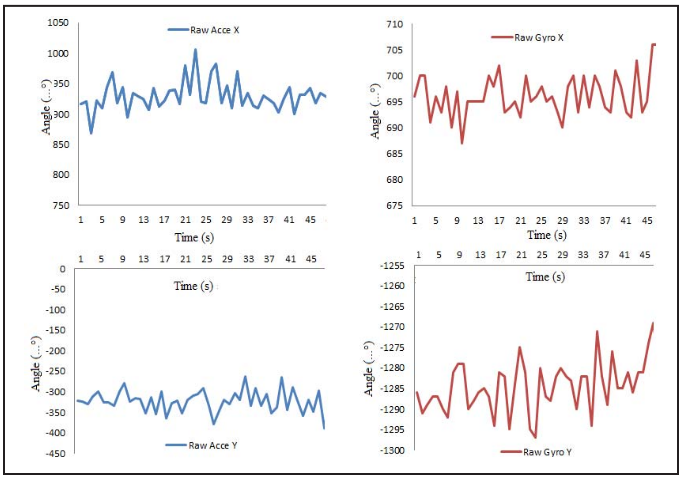

Fig. 6. Raw data of Accelerometer and Gyroscope at real-time captured via PLX-DAQ before filter.

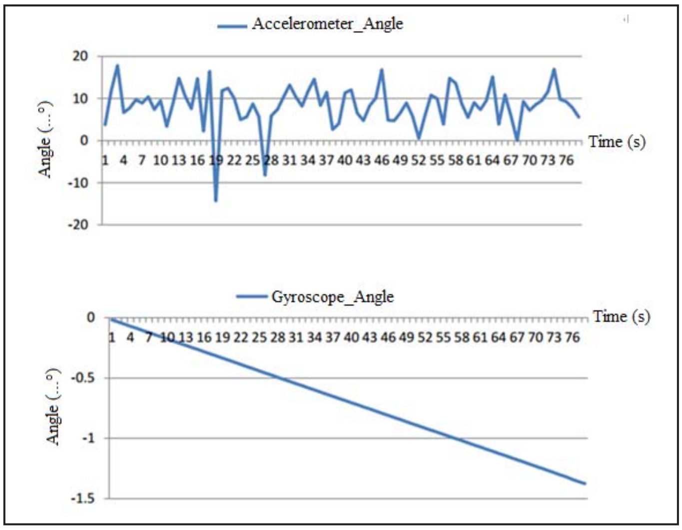

Fig. 7. Data of Accelerometer and Gyroscope after converted in angle value.

Figure 7 reveals a clear trend of accelerometer sensibility to noise while the gyroscopes experienced drift angle where in reality it is in static condition with zero angle. This clearly proves that the both gyroscope and accelerometer requires a filter to ensure the output free of interference. Factor value, a will be tuned in order to find the best value where simple rotation along X-axis approximately 0 to 100 degrees is done throughout the whole experiment. The results obtained from the preliminary analysis of different constant setting complementary filter for angle at X-axis and Y-axis are compared in below four figures, Figures 8,9,10,11 and 12.

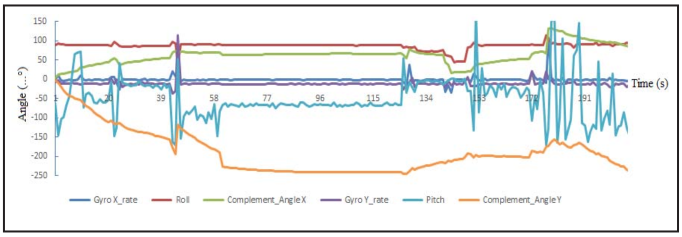

Fig. 8. Angle X measurement response at real-time using complementary filter with factor a = 0.95.

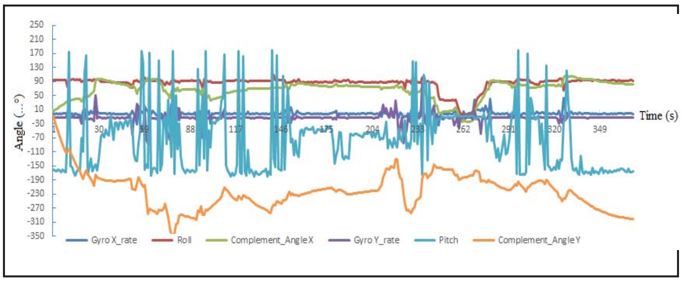

Fig. 9. Angle X measurement response at real-time using complementary filter with factor a = 0.96.

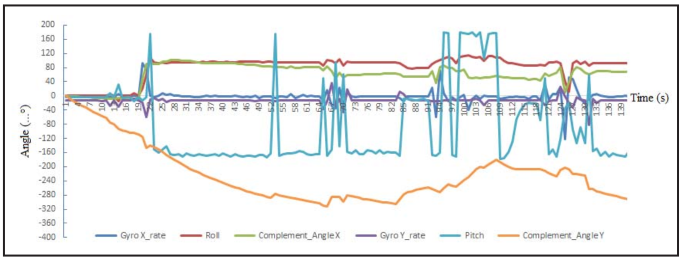

Fig. 10. Angle X measurement response at real-time using complementary filter with factor a = 0.97.

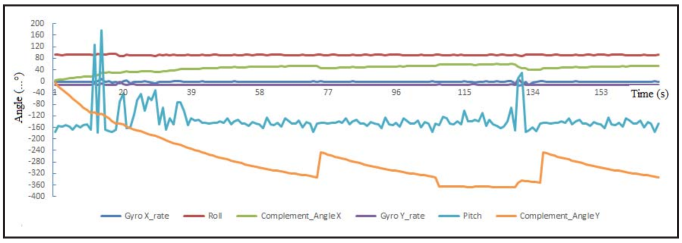

Fig. 11. Angle X measurement response at real-time using complementary filter with factor a = 0.98.

From the four graphs, the red line shows the accelerometer data (roll) with spikes which consist of a noisy data set. The blue line provides the rotation angle calculated from summing the individual angles read from the gyroscope. It can be seen in all four captured graphs, the gyroscope prone to drift over time and doesn't return back to zero when it's in static condition. The green line shows the complementary filter. It combines the two data sets by merging fast rotations from the gyroscope with the slower trends from the accelerometer.

In complementary filter system, each iteration roll angle values will be updated with the new gyroscope values by means of integration over time. The filter then compare with the magnitude of the force produced by the accelerometer for acceptable value. Supposing that the value is either too small or too big, no doubt the signal consists of disturbance and it will not be considered. Then the filter system will update the pitch and roll angles with the accelerometer data based on setting of the factor value, *a*.

As in Figure 11, the factor value for complementary filter of *a* is assigned with 0.98. Hence, once the complementary filter system compare the current gyroscope value with magnitude of the force, the filter will revise the pitch and roll angles with the accelerometer data by taking 0.98 of the current value, and summed with 0.02 of the angle computed by the accelerometer. This technique is to establish a stable system with measurement which prone to drift and manage to produce accurate angle in the short term.

It is apparent from graph in Figure 11, the red line shows the roll accelerometer data and as we can see from the spikes it's a noisy data set. The blue line show the rotation angle detected from the gyroscope with drift over time, and the complementary filter (green line) did not return to zero even in reality the sensor is not moving. In addition,

Throughout the experiment, the best filter factor $a = 0.97$ is chosen as it can be seen in Figure 12, the complementary filter (green line) constantly follow the mean value of the roll accelerometer (red line) without spike signal of noise accelerometer and far from drift over time.

IV. CONCLUSION

It has been proven by integrating the hardware system with the development of the digital complementary filter for MEMS gyroscope and accelerometer to measure angle at the accurate level has been successfully and accurately developed. Based on the experimental and analytical results, it was found that the developed system is able to filter and measure desired position level of 0 to 100 degrees, consistently. Experimental results also proven that drift and can be filtered without any difficulty by using complementary filter. Thus, this will help to improve the MEMS gyroscope and accelerometer to sense the actual angle with position accurately and consistently without fail. As a result, the development of a complementary filter system assisted for angle estimation can be applied to improve angle detection consistently and accurately.

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