Design of AHRS for Quadrotor Control using Digital Motion Processor

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***Abstract*—Quadrotor is one type of UAV (Unmanned Aerial Vehicle) that uses four motors to drive the propellers. Commonly, quadrotor has inertial sensors or Inertia Movement Unit (IMU), which is a source of data to obtain information attitudes and three-dimension orientation or so-called Attitude Heading Reference System (AHRS). This study used Digital Motion Processor (DMP) technology that can perform filter process and an accurate calculation AHRS independently by reducing the calculation process on the microcontroller. The data generated from the DMP were in the form of four-dimensional quaternion and filtered data sensor. In this paper, the discussion focuses on the DMP technique and AHRS comparison. Hardware design, embedded systems and data communication were also included to complete the overall system design quadrotor. The results show that angular position measurements of DMP have less noise than the direct measurement of sensor accelerometer and gyroscope. AHRS obtained from DMP has similar result with the calculation result of Mahony's AHRS algorithm and Madgwick's AHRS algorithm. The proposed design utilizes the DMP technology capable to control quadrotor well.**

***Index Terms*—Quadrotor; Attitude Heading Reference System; Digital Motion Processor.**

I. INTRODUCTION

A quadrotor that uses four rotors to obtain thrust is one of the famous VTOL (Vertical Take-Off and Landing) or UAV (Unmanned Aerial Vehicle) systems. These systems have been successfully applied in a broad field, such as construction, search and rescue in disaster regions, aerial transport of payload, video shooting, etc. In addition, this system is suitable for both civil and military missions such as fire detection of forest, traffic surveillance, and enemy surveillance [1][2].

Many exciting developments appeared in the literature are classified in diverse categories: modeling, control law design, software and hardware development, trajectory tracking, and navigation. The objective of the current research effort is to design a UAV system, which is competent for conducting further investigation in the fields of guidance, navigation, and control [3].

An Attitude and Heading Reference System (AHRS) is one of the most critical parts in controlling quadrotor that requires the accuracy of speed while maintaining balance. However, procedure and calculations processes for data sensor are needed to obtain an accurate AHRS filters [4]. A new AHRS needs to be developed to solve this problem. Several methods have been offered to address this issue, such as the direction cosine matrix (DCM) algorithm [5], Complementary Filter (CF) [6], Kalman Filter and, Extended Kalman Filter (EKF) [7], Madgwick algorithm [8], or Mahony algorithms [9].

Motivated by these considerations, this paper offers a method for generating AHRS output using Digital Motion Processor (DMP). The data generated from the DMP are in the form of four-dimensional quaternion data. The DMP is used as a regulator for the balance of angular position, while the barometer is used as a sensor height adjustment., the ground control is designed as a control center using a laptop, and a joystick as control inputs. Several experiments have been performed to prove the performance of the proposed method.

II. THEORETICAL BACKGROUND

A. Quadrotor Motion Principle

Quadrotor movement mechanism is a resultant of propeller rotation speed (ω1, ω2, ω3 and ω4). This composition generates force on each rotor (F1, F2, F3 and F4) that affects the translational or rotational motion of the quadrotor body. The coordinates and motion principle of the quadrotor are depicted in Figure 1 [10].

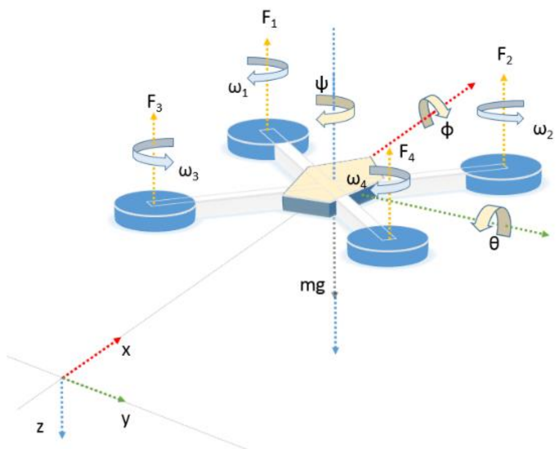

Figure 1: Schematic view of the quadrotor: coordinates and motion principle

Equation (1) is a total lifting force to be generated by the motor to allow the quadrotor to hover. Equation (2) and (3) also show the condition of quadrotor to lift up or down, respectively [10].

$$F_1 + F_2 + F_3 + F_4 = W = m \times g = FT \quad (1)$$
$$F_1 + F_2 + F_3 + F_4 > W \quad (2)$$
$$F_1 + F_2 + F_3 + F_4 < W \quad (3)$$

Figure 2 shows the movement of a quadrotor in relation to each angular speed of motor [10].

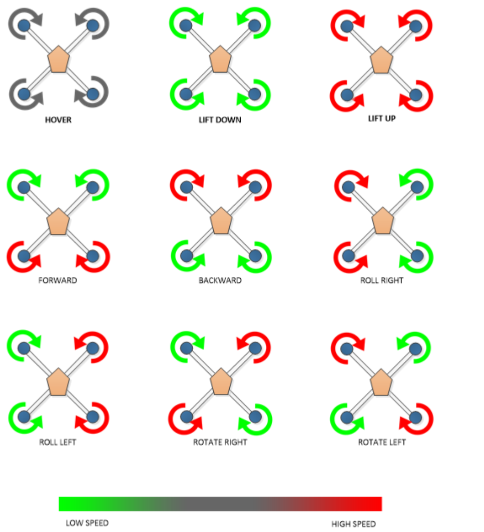

Figure 2: Coordinates and movement principle of quadrotor

B. Quaternion Data

Quaternions refer to an algebraic system extended from the complex numbers that was first introduced by Irish mathematician William Rowan Hamilton in 1843. A classic application of quaternions is used to replace Euler angles for attitude description of rigid bodies and computer graphics. Quaternions are mathematically denoted as in Equation (3), where q0, q1, q2, and q3 are all real numbers. It is commonly known that the three rotations around different axes defined by Euler angles can be replaced with one rotation around a certain vector in the reference frame. A quaternion is capable of describing that rotation just right [11]:

$$\boldsymbol{q} = q_0 + q_1\boldsymbol{i} + q_2\boldsymbol{j} + q_3\boldsymbol{k} \tag{4}$$

$$\boldsymbol{q} = [q_0 \quad q_1 \quad q_2 \quad q_3]^T \tag{5}$$

Two quaternion data, *p* and *q*, were multiplied using Kronecker Product, which is marked by ⊗. Then, two rotation are shown as p⊗q rotation.

$$\boldsymbol{p} \otimes \boldsymbol{q} = \begin{bmatrix} p_0q_0 - p_1q_1 - p_2q_2 - p_3q_3 \\ p_0q_1 + p_1q_0 + p_2q_3 - p_3q_2 \\ p_0q_2 - p_1q_3 + p_2q_0 + p_3q_1 \\ p_0q_3 + p_1q_2 - p_2q_1 + p_3q_0 \end{bmatrix} \tag{6}$$

while

$$\boldsymbol{p} \otimes \boldsymbol{q} \neq \boldsymbol{q} \otimes \boldsymbol{p} \tag{7}$$

Magnitude on Quaternion:

$$\boldsymbol{Magnitude}(\boldsymbol{q}) = \|\boldsymbol{q}\| = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2} \tag{8}$$

Conjugation on Quaternion:

$$\boldsymbol{Conj}(\boldsymbol{q}) = \boldsymbol{q}^* = [q_0 \quad -q_1 \quad -q_2 \quad -q_3]^T \tag{9}$$

Inverse on Quaternion:

$$\boldsymbol{Inv}(\boldsymbol{q}) = \boldsymbol{q}^{-1} = \frac{q^*}{\|q\|^2} \tag{10}$$

Normalization on Quaternion:

$$\boldsymbol{Normalize}(\boldsymbol{q}) = \begin{bmatrix} \frac{q_0}{\|\boldsymbol{q}\|} & \frac{q_1}{\|\boldsymbol{q}\|} & \frac{q_2}{\|\boldsymbol{q}\|} & \frac{q_3}{\|\boldsymbol{q}\|} \end{bmatrix}^T \tag{11}$$

So, 3D vector rotation as:

$$\vec{\boldsymbol{w}} = \boldsymbol{q} \otimes \begin{bmatrix} 0 \\ \vec{\boldsymbol{v}} \end{bmatrix} \otimes \boldsymbol{q}^* \tag{12}$$

$$\boldsymbol{q} = \begin{bmatrix} \cos\left(\psi/2\right)\cos(\theta/2)\cos\left(\phi/2\right) + \sin\left(\psi/2\right)\sin(\theta/2)\sin\left(\phi/2\right) \\ \cos\left(\psi/2\right)\cos(\theta/2)\sin\left(\phi/2\right) - \sin\left(\psi/2\right)\sin(\theta/2)\cos\left(\phi/2\right) \\ \cos\left(\psi/2\right)\sin(\theta/2)\cos\left(\phi/2\right) + \sin\left(\psi/2\right)\cos(\theta/2)\sin\left(\phi/2\right) \\ \sin\left(\psi/2\right)\cos(\theta/2)\cos\left(\phi/2\right) - \cos\left(\psi/2\right)\sin(\theta/2)\sin\left(\phi/2\right) \end{bmatrix}$$

$$\begin{bmatrix} \psi \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} \operatorname{atan}(2(q_1q_2 + q_0q_3)/(q_0^2 + q_1^2 - q_2^2 - q_3^2)) \\ \operatorname{asin}(2(q_0q_2 - q_3q_1)) \\ \operatorname{atan}(2(q_0q_1 + q_2q_3)/(q_0^2 - q_1^2 - q_2^2 + q_3^2)) \end{bmatrix}$$

To obtain the offset between q_A and q_B, q_offset was calculated as q_A by conjugation with q_B as in Equation 10. Kronecker multiplication was used to generate offset of each axis rotation.

$$\boldsymbol{q}_{offset} = \boldsymbol{q}_A \otimes \boldsymbol{q}_B{}^* \tag{13}$$

C. AHRS

Attitude Heading Reference System (AHRS) is a 3-axis sensor system that provides three-dimensional position information orientation (yaw, pitch and roll) in real time. The main function of the AHRS is to provide data orientation. AHRS consists of a magnetometer, accelerometer and gyroscope on all of the three axes. These sensors create inertial sensor system that can fully measure the attitude of objects in 3D space.

The basic technique for calculating AHRS system is based on measuring the sensors directly, which is so-called Direct AHRS. Then, several techniques were developed to improve the accuracy and calculation process of AHRS. Some of these techniques include: Complementary Filter (CF), Kalman Filter, Extended Kalman Filter (EKF), the algorithm direction cosine matrix (DCM), Mahony algorithm, or algorithms Madgwick [4-9].

D. DMP

Digital Motion Processor is a technology planted on inertial sensor chip that is intended to process the data sensor. The technology can filter the data and process complex calculations quickly. In fact, this technology is able to process sensor data from other chips. A chip that has been implemented with technology DMP is MPU9x50. Fig. 1 shows a block diagram of the chip.

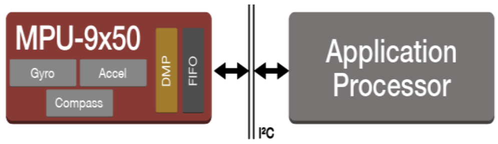

Figure 3: Block diagram of MPU-9x50

In Figure 3, the chip MPU9x50 has a gyroscope sensor, accelerometer and compass. The data measurements from the sensors were processed by the DMP. Then, the results of the calculations were stored in the FIFO buffer. If the FIFO buffer is ready to be read by the microcontroller, the chip provides an interrupt signal. DMP data packets are measurement data that has been filtered and formed as quaternion data that have a 46 bytes number.

III. System Design

Typical quadrotor system contains a UAV quadrotor, a ground control and a communication system [12]. The whole system is shown in Figure 4. Figure 5 shows the block diagram of the developed system.

Figure 4: A whole system of the UAV quadrotor

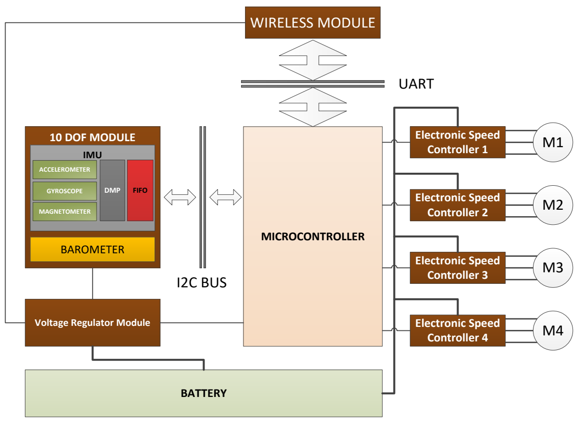

Figure 5: Block diagram of quadrotor system

The UAV system design consists of a frame, motors and propellers as actuators, microcontroller unit as a control module, IMU unit as AHRS data source and wireless unit as supporting communication with ground control.

Typically, it includes the following components: the brushless dc motor (BLDC), the propeller, the Electronic Speed Controller (ESC) and the battery. Aggressive maneuver requires high thrust-quality ratio and fast response. The BLDC motors used was the Motor SunnySky X224S-16 with 2300kV, and it needs 11.v Volt. The maximum speed is 25530 rpm. ESC EMAX12 A was used for speed controller that has PWM input signal and internal Battery Eliminator Circuit (BEC) with 5V/1A rate. Six propellers HQ-PROP were used with 6-inch long and 3-inch pitch. A microcontroller system based on Arduino Pro mini with ATMega328 was used to control all quadrotor system. For aggressive maneuver, the body is supposed to be light, strong, and small inertial. The quadrotor was designed in X-frame type of FPV250 with diameter 25 cm and weigh 109 g. The placement of four motors on this frame had the same distance to the center of mass quadrotor.

In this design, the sensors were organized in a reasonable way. Drotek 10 DOF IMU that contains accelerometer, gyroscope, magnetometer and barometer was used. The sensor system contains two chips, MPU9150 that contains accelerometer, gyroscope, magnetometer and MS5611-01BA that contains barometer. A DMP system was mounted in this unit.

Wireless communication is one of the challenges in this method. Several factors were taken into consideration such as power consumption, weight, transmission speed and reliability. Modules XBee Pro 900 HP is one of the modules suitable to support these criteria. XBee Module Explorer was used to simplify the circuit and connectivity with a microcontroller or computer.

The sensor unit is the focus in this research. The sensor unit processed the data based on IMU results which is named as AHRS. The results were angular position, rotational speed, acceleration and altitude. The data were used to process the flight control in advance.

There were several correction calculations between the body frame of IMU, qdmp, and the body, qbody to know real angular position. Figure 6 shows the process and, as displayed in Figure 7, another manipulation was done to produce the rotational speed and acceleration.

Then, AHRS data were used in the flight controller based on PID schema. Outputs from the flight controller were then distributed to BLDC motor, respectively. Two modes of flight controller were designed as acrobatic mode and angle mode. Acrobatic mode utilizes the angular velocity as the equilibrium position, while the angle mode utilizes the angular position as a reference to maintain the angular position and angular velocity using as equilibrium position.

Finally, a special software was prepared to test DMP process and results. The test compared some algorithms of AHRS with DMP. The results of this calculation were stored in Excel file.

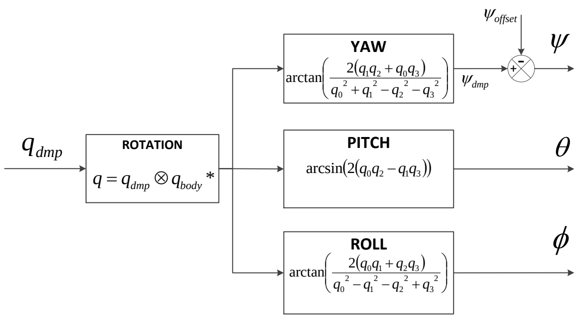

Figure 6: Angular position calculation

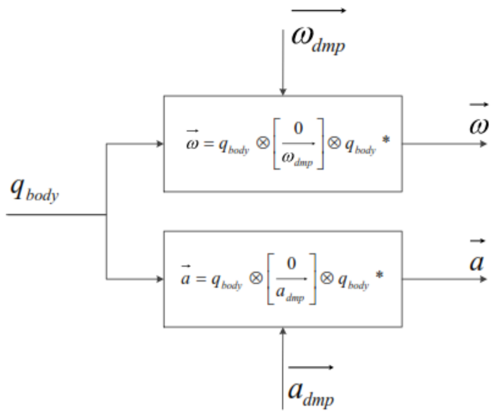

Figure 7: Rotational speed and acceleration calculation

IV. Result And Discussion

The whole of UAV quadrotor based on the system design described above is depicted in Figure 8. The UAV system design consists of a frame, motors and propellers, microcontroller unit, IMU unit and wireless unit. The detail of IMU unit and DMP is shown in Figure 9. Figure 10 shows a general quadrotor control system. PC / Notebook connected with XBee module and an Xbox joystick were used as input for flight control.

Several experiments have been performed. The first experiments was to test the ability of the quadrotor to move up, hovering and down. In this experiments, the input throttle was set on 900 to 2000, with an increase of 100 at every 3 seconds. The results of this experiments are shown in Figure 11.

Figure 11 shows that if the throttle inputs are between 900 and 1499, the quadrotor will fly down because the thrust in this area are below from the quadrotor weight. However, the quadrotor will fly up if the throttle input are above 1500, because the thrust are above from the quadrotor weight. When the throttle is around 1500 and the thrust is almost equal to quadrotor weight, it will be hovering. Based on this, it can be said that the UAV quadrotor has the ability to be controlled by maneuvering it up, down and hovering it well.

Next, are the results of the angular position calculation. These experiments were based on the DMP technique as described and is shown in Figure 12. The performance of DMP were compared with other techniques, such are Direct AHRS, Complementary Filter, Kalman Filter, DCM, Mahony and Madgwick.

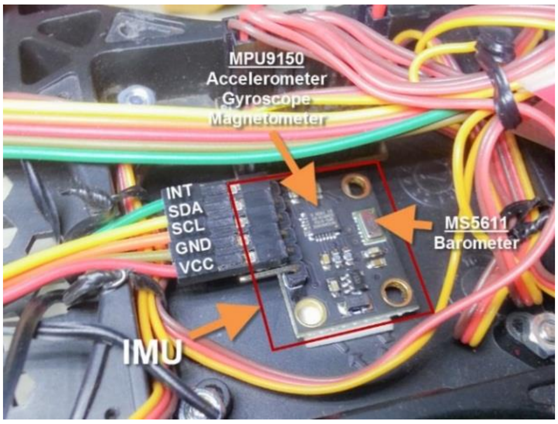

Figure 8: A UAV quadrotor system

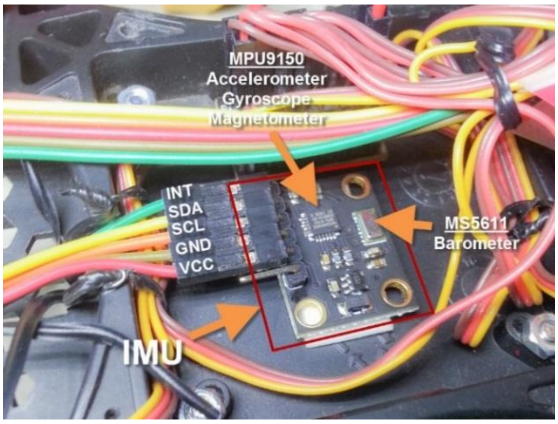

Figure 9: IMU unit and DMP

Figure 12, 13 and 14 show the comparison of angular position of raw, pitch and roll based on DMP and Direct AHRS. These figures showed that the angular positions with DMP are smoother and faster than Direct AHRS technique. The mean of absolute deviations of DMP with Direct AHRS were 19.640, 13.290, and 16.020 for yaw, pitch and roll, respectively.

Figure 10: A UAV and ground control

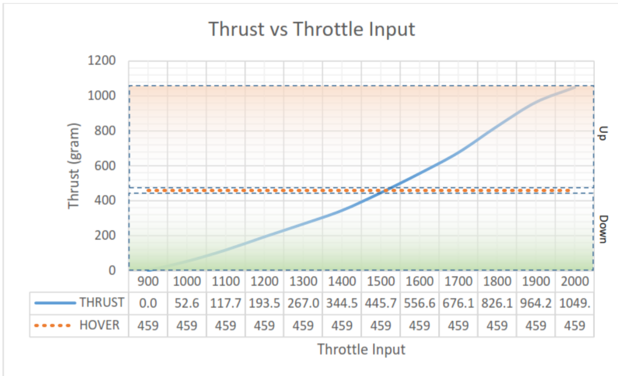

Figure 11: A UAV quadrotor maneuver test

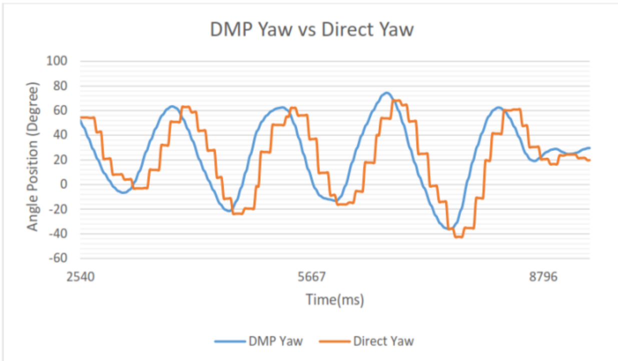

Figure 12: Angular position: DMP yaw vs. direct AHRS yaw

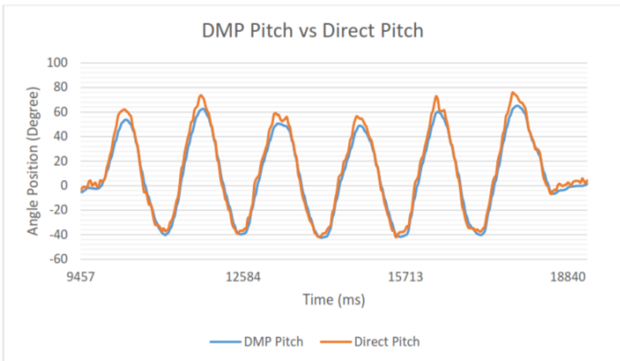

Figure 13: Angular position: DMP pitch vs. direct AHRS pitch

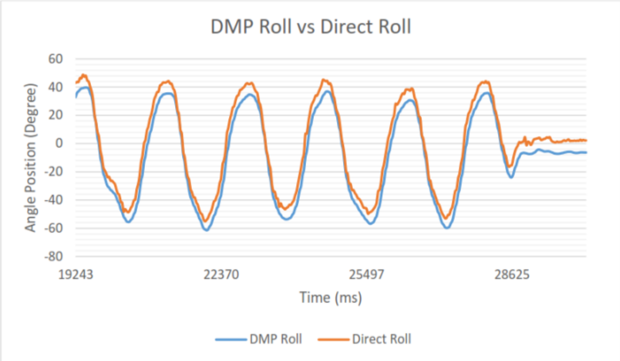

Figure 14: Angular position: DMP roll vs. direct AHRS roll

The comparison of the angular position of raw, pitch and roll based on DMP and Madgwich technique are displayed in Figure15, 16 and 17. Although the patterns of both techniques are almost the same, there are still differences in the angular position value. The mean of absolute deviations of DMP with Madgwich technique are 4.330, 5.370, and 8.500 for yaw, pitch and roll, respectively.

All mean of absolute deviation of DMP and another techniques are listed in Table 1. Based on that table, it can be said that DMP technique has a promising result. There are significant absolute deviations for almost all techniques with more than 50. Also it has almost the same performance with Mahony and Madgwick techniques. DMP technique has significant benefits in scale and processing time.

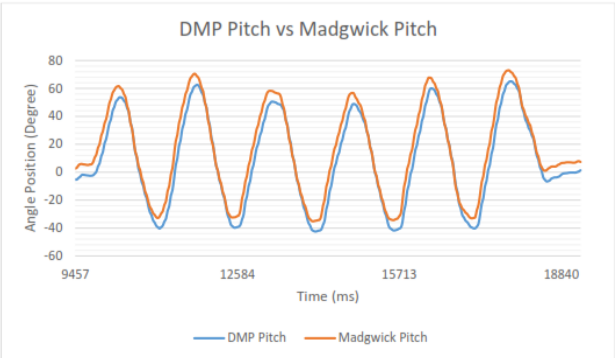

Figure 15: Angular position: DMP roll vs. Madgwick pitch

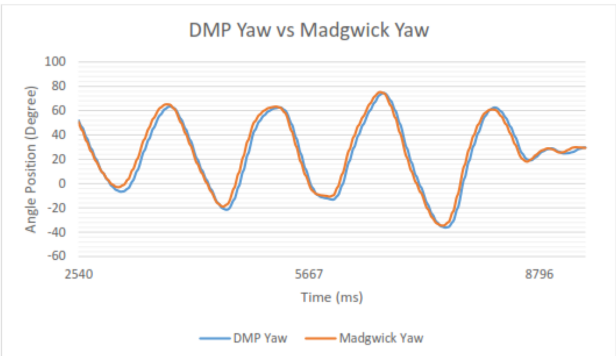

Figure 16: Angular position: DMP roll vs. Madgwick yaw

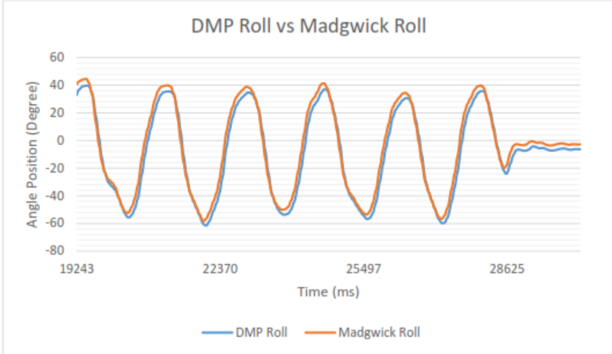

Figure 17: Angular position: DMP roll vs. Madgwick roll

V. CONCLUSION

A UAV quadrotor with x-frame type has been designed. The UAV system design consists of a frame, motors and propellers as actuators, microcontroller unit as a control module, IMU unit as AHRS data source and wireless unit as supporting communication with ground control. A DMP technique to produce AHRS data for angular position calculation was used. Several experiments have been performed. It can be concluded that the quadrotor is able to maneuver in flying up, down and hovering. In conclusion, the DMP process has promising results. There are significant absolute deviations of angular position of DMP results compare with another techniques of AHRS processes.

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Table 1
Mean of Absolute Angular Deviation of DMP and other Techniques

Angular Position (^{0})	AHRS Methods					
	Direct AHRS	Complementary Filter	Kalman Filter	DCM	Mahony	Madgwick
Yaw	19.64	11.61	20.03	23.04	4.43	4.43
Pitch	13.29	12.82	8.00	26.38	5.32	5.37
Roll	16.02	15.73	10.13	17.61	6.6.3	8.50