# Design of Quadrotor Hovering System Based on Inertial Measurement Unit Sensor

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*Abstract* — **The dynamic flight of quadrotor is more free than other aerial vehicles especially in hovering. Quadrotor require sensors and control process to achieve stable attitude on hovering. Inertial Measurement Unit (IMU) sensor was used to determine the attitude (pose) of quadrotor. In this project, there were two IMU sensor which was used as a reference. They were YEI 3 Space Sensor and Ardupilot Mega 2.5 (henceforth abbreviated as APM 2.5). Some of the testing process was performed on these sensors to determine where the sensor were suitable for Quadrotor. By sensing the attitude of Quadrotor, the control process can be carried out. Simple PID controller was implemented in this project. The control process was carried out on four axes of the quadrotor i.e pitch, roll, yaw, and altitude. The controller was used so that the quadrotor capable of hovering steadily at a height of 15 cm. The test results showed that the IMU sensor on Ardupilot Mega 2.5 is more suitable for use in Quadrotor because it has a smaller RMS error than YEI 3 Space Sensor when used in Quadrotor environments. According to the experiment, the RMS error of the IMU sensor on Ardupilot Mega was less than 1$^o$ and the RMS error of the APM 2.5 was more than 1$^o$. PID controller with filtered derivative output action has an error of 5 degrees (from set point) and drifting effect appeared when this controlled was performed.**

**Keyword – quadrotor, inertial measurement unit, hovering**

## I. PRELIMINARY

Quadrotor is one of Unmanned Aerial Vehicles which have many advantages including the form of simple construction and flight dynamics are more free than other aircraft types. Quadrotor have an ability such as vertical takeoff and landing like a helicopter and do a lot of maneuvers like fixed wing aircraft. Because of that, Quadrotor widely applied as a surveillance robot, rescue, and other military purposes. Hovering is one of the movement of quadrotor. The flight of quadrotor so that it can float at one point steadily is called hovering. Quadrotor require a reliable IMU sensor and complex control systems for stable hovering. IMU sensor is a sensor used to determine the orientation of the Quadrotor. This orientation is expressed in 3-axis that named by pitch, roll, and yaw.

Bardo Wenang, in his paper proposes the use of a simple PID controller based on proximity sensor. The attitude of Quadrotor was known by the height of the each motor that is measured by a proximity sensor. The value of sensor readings feedback to the PID controller. [1]

Knowing the attitude by using the proximity sensor is only effective to a certain height and the base should be flat and bright so that the proximity sensor is able to work effectively. In addition, Knowing the attitude by using a distance or proximity sensor readings only get pitch and roll angles. The proximity sensor can not determine the yaw angle or the heading of Quadrotor.

In this project, to determine the attitude of a Quadrotor using Inertial Measurement Unit (IMU) sensor which consists of a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetomer. The output of IMU sensor readings is the attitude in the axis of pitch, roll, and yaw. By using the IMU sensors, the attitude of quadrotor can be controlled at any height and has no effect on the base of the Quadrotor. The yaw axis or heading of Quadrotor can also be controlled. To be able to control the attitude well, it takes a reliable IMU sensor. There are many IMU sensors sold in the market. In this project, there are two IMU sensor which is used as a reference for use Quadrotor. They are YEI 3 Space Sensor products from Yost Engineering and Ardupilot Mega 2.5 products from 3D Robotics.

Muhammad Alfiansyah in his paper stated that IMU sensor readings are susceptible to noise due to vibration. It can affect the outcome of the accelerometer readings. Furthermore, IMU sensor was also at risk of drifting that caused by gyroscope. Based on his paper, it is necessary to test the effects of both the sensor noise and drifiting. IMU sensor which has a smaller error readings will be used as orientation sensor in Quadrotor. [2]

Beside attitude, another variable that must be controlled in the process is altitude of the Quadrotor. Altitude is the height of the Quadrotor. The height of Quadrotor was sensed by SRF04 ultrasonic sensor.

IMU sensor readings and altitude is fed to the PID controller. The output of the PID controller is used to control the speed of the four motors of Quadrotor using the value of the duty cycle PWM signal. During the unstable position of the Quadrotor, it will determine how much the PID output as motor speed is raised or lowered so Quadrotor became stable.

## II. SYSTEM DESIGN

Block diagram of quadrotor hovering system design can be observed in Figure 1. Quadrotor has two sensor inputs which consist of IMU sensor of Ardupilot Mega 2.5 and SRF04 ultrasonic sensor. IMU sensor issue data from Quadrotor attitude. This attitude data covering angles pitch, roll, and yaw. As for the SRF04 is used to read the altitude (height) of the quadrotor.

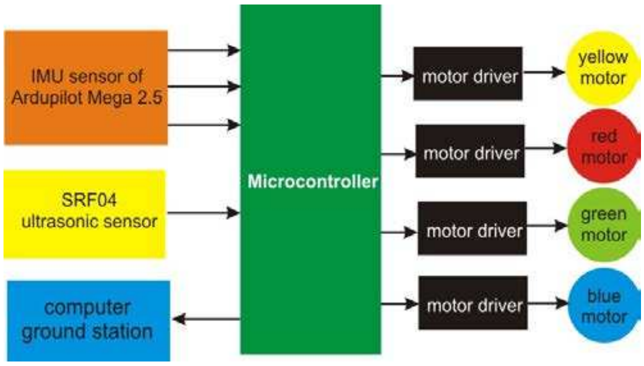


Figure 1. Block diagram of Quadrotor hovering system

The sensor readings that have been acquired by the microcontroller not only to be input of the PID controller but also sent to the computer via bluetooth for monitoring purposes. The output of PID controller was the duty cycle of PWM signal and then used to control the speed of DC motor through the motor driver.

*A. Quadrotor Hardware Design*

Hardware design consists of designing the basic framework Quadrotor, IMU sensors, ultrasonic sensors, microcontrollers, motor driver circuit and power supply. The quadrotor frame that used in this project was a product output of Draganflyer IV. Quadrotor in this project consists of a frame kit, four propeller, four brush DC motors, four pieces of gear. All of the parts of the quadrotor are arranged into basic framework as shown in Figure 2.

Frame 2. Draganflyer Quadrotor frame product

APM 2.5 board products from 3D Robotics was used. Ardupilot Mega 2.5 is a complete autopilot system. This project used only IMU sensor and mikrokotroler ATMega 2560. Function of microcontroller ATMega 2560 was acquiring data from the IMU sensor then process it using sensor fusion algorithms and Kalman filter to obtain data such as angle of pitch, roll, and yaw. Then, this attitude data is sent to the STM32F4 microcontroller via USART communication for control process in Quadrotor.

APM 2.5 board was placed in the middle of the quadrotor's frame as shown in Figure 3. APM 2.5 board was placed such that the frame that connects the red and yellow motor was pitch axis and frame that connects the green and blue motor was the roll axis. The plane of the picture is the yaw axis. SRF04 ultrasonic sensor is used as the altitude sensor (height). It was placed at the center of the Quadrotor and precisely under the APM 2.5 board.

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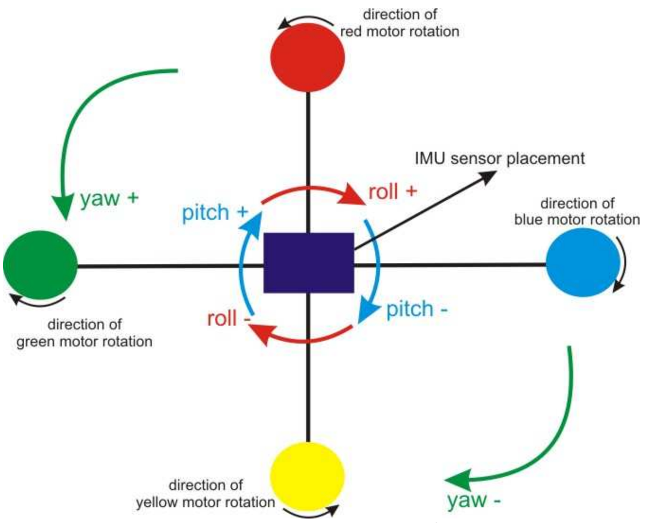


Figure 3. IMU sensor placement and orientation of Quadrotor

Circuit driver that was used in this project was n-channel MOSFET IRFZ44N and PC817 optocoupler. Each DC motor was controlled by a pair of IRFZ44N and PC817. PC817 optocoupler was used to isolate microcontroller circuit from DC motors. So there are two supply that worked on motor driver and microcontroller with a separate ground.

*B. Quadrotor Software Design*

The software was designed on the microcontroller STM32F4 and Ardupilot Mega 2.5 platform.

Software design used APM 2.5 Arducopter firmware version 2.9 which was developed by diydrones team. Some libraries from this firmware have a several function such as sensor data acquisition and AHRS IMU data processing, these overall proces took 35 ms . In essence, APM 2.5 board was programmed to do several operation such as calculating AHRS data and sending AHRS data to the microcontroller STM32F407 via USART communication protocols. The data that was sent to the microcontroller consist the value of pitch, roll, and yaw axis with data length of 12 bytes every 35 ms. Baud rate of the communication was at 115200 bps.

Overall, the program begins with the initialization USART1 to read data from the IMU sensor, USART2 transmit sensor measurement data to a computer, external interrupt and timer to read the data from the sensor SRF04 altitude, and initialize the timer to generate PWM signals.

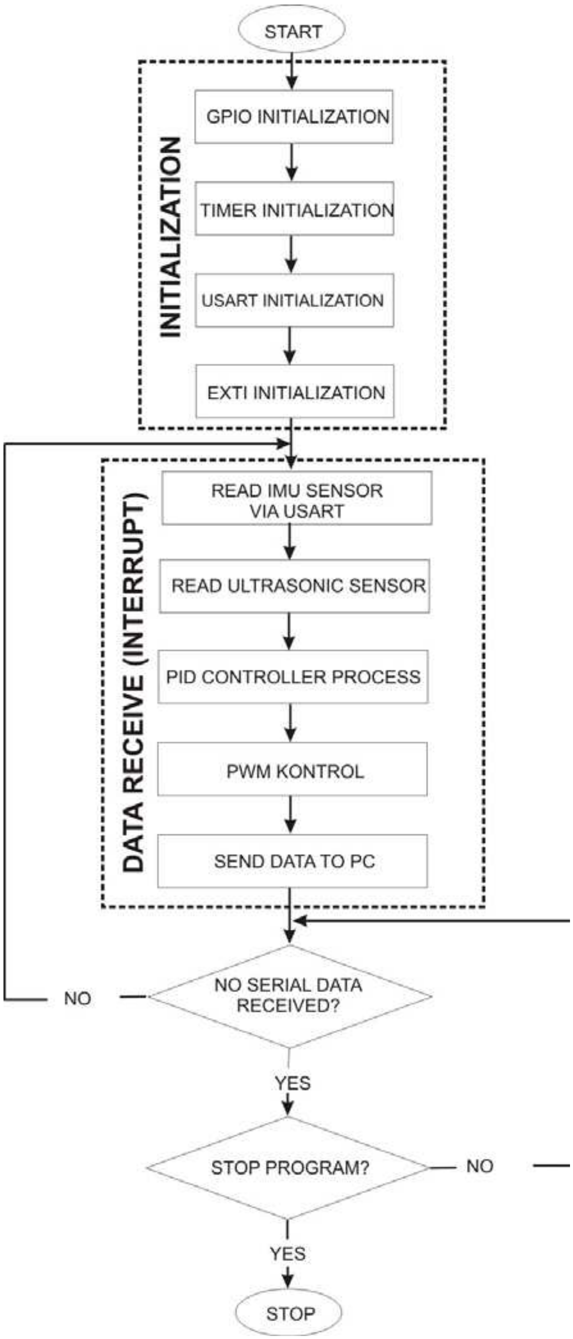


Figure 4. STM32F4 Microcontroller Program Flowchart

One full cycle was started from the sensor readings, continued with process control, until DC motor actuation. One cycle was done in 35 ms intervals. Time base of 35 ms was not raised by the timer of STM32F407 microcontroller itself but it was determined by setting the timing of APM 2.5. IMU sensor data will be sent by the APM 2.5 to STM32F407 microcontroller once every 35 ms. These data has already in AHRS format. USART on STM32F407 settings for communication with APM 2.5 using the receive interrupt mode. Therefore, if the STM32F407 microcontroller receives data from APM 2.5, the process of the sensor readings , control , actuation DC motor to be done automatically . Sensor readings that have been received subsequently fed into the digital PID controller that has been programmed in STM32F4 microcontroller. PID controller output a control signal used to control the speed of a DC motor . Controller output is expressed in terms of duty cycle of the PWM signal generated by microcontroller timer of STM32F4.

## C. PID Controller

There were four independen digital PID controller in the project.Each PID controller controlled dynamic motion of the quadrotor in pitch, roll, and yaw axis plus altitude. Digital PID controller was programmed on STM32F4 microcontroller. There were three different PID controller that used in the experiment. This three PID controller block diagram shown in figure 5.

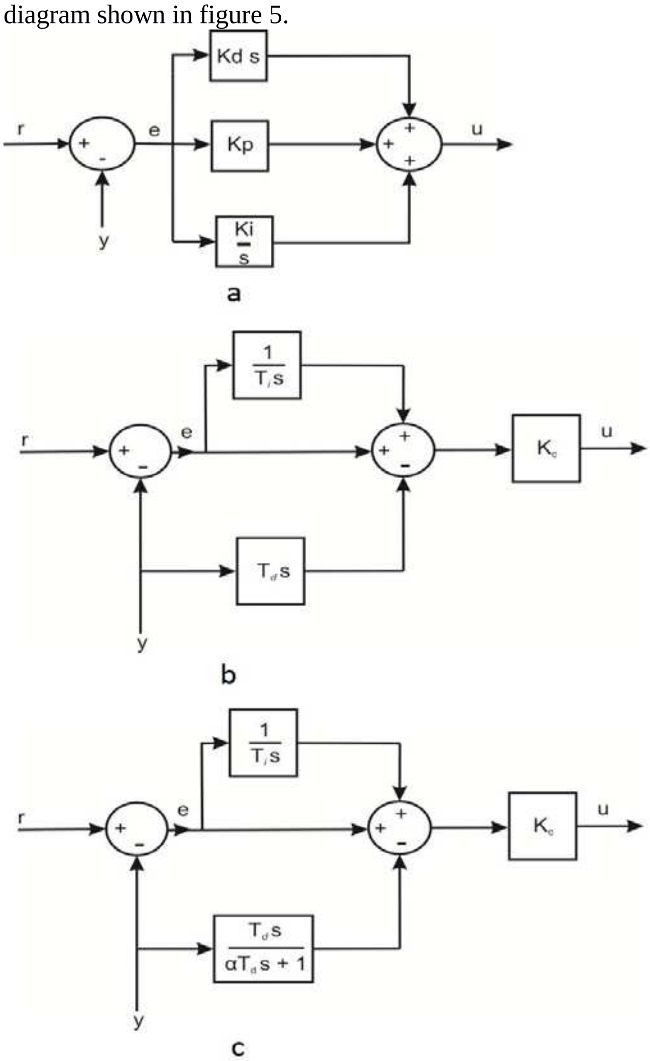


Figure 5 PID controller mode (a) 1, (b) 2, (c) 3 [3]

The input of PID controller for pitch, yaw, and roll angles from the IMU sensor readings expressed in degrees. The controller set point for the pitch and roll axis was zero degrees. While the set point for the yaw axis was the initial value itself. Altitude controller had the input of ultrasonic distance sensor readings and set point in the form of the desired height. Output of each controller was the duty cycle of the PWM to control the motor speed.

Based on quadrotor orientation diagram in Figure 3, the relationship between the four sensor inputs with four outputs in the motor control system as a whole can be seen in the following block diagram.

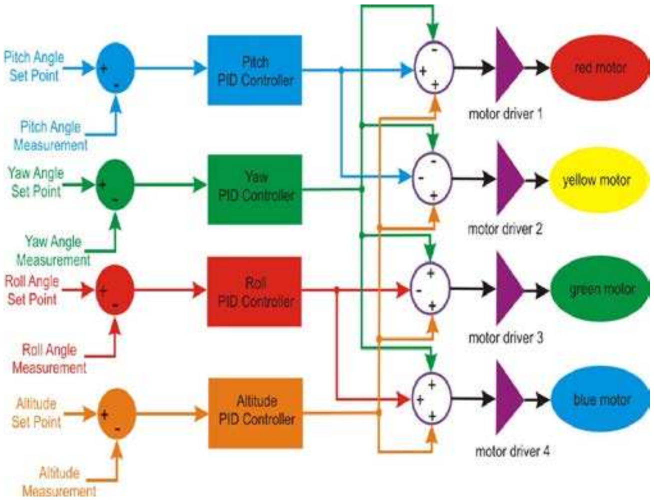


Figure 6. Quadrotor PID Controller Block Diagram

## III. Test and Analysis

This chapter presented the results of test and analysis system. The test is performed in hardware and software, especially on the sensor and kontoler. This test will produce an image signal to be analyzed.

### A. *IMU Sensor Test*

IMU sensor test was conducted to determine the quality of the sensor. This project used two sensors: YEI 3 Space IMU sensor and IMU sensor on APM 2.5 module. Sensor witch the best performance would be used to Quadrotor. There were several stages of testing sensors by comparing the sensor readings with a protractor, test the sensor resistance to noise in the environment Quadrotor, testing the cross-axis effects of IMU sensor. Both IMU sensors got the same treatment at each stage of testing.

The first test was the calibration of the sensor readings with reference protractor. This test aimed to determine the accuracy of the sensor readings by comparing the sensor readings with a protractor. Sensor readings was performed on three rotary axes (pitch, roll, and yaw). Each sensor was placed on a flat board. Furthermore the board flat tilted towards protractor as in Figure 7 and data from sensor readings displayed on the computer.

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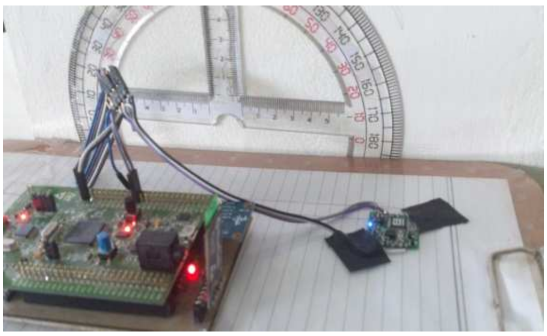

Figure 7. IMU sensor calibration

Error value is obtained from the difference between the sensor readings with a protractor measurement results. By taking 11 samples for pitch and roll axes and 13 samples for the yaw axis, the value of the RMS error for both sensors are presented in Table 1.

Table 1
RMS error value for IMU sensor calibration

| | *Pitch RMS Error* | *Roll RMS Error* | *Yaw RMS Error* |
|---|---|---|---|
| YEI 3 Space | $4{,}47^o$ | $0{,}63^o$ | $14{,}34^o$ |
| APM 2.5 | $0{,}45^o$ | $0{,}52^o$ | $3{,}34^o$ |

It can be observed that the RMS error value of each axis on IMU sensor APM 2.5 has a smaller value than YEI 3 Space sensor for all axes. Error values were high on YEI 3 Space sensor readings can be caused by the data output from the sensor is not the degree but radians. Error may occur in the conversion process from radians into degree. From this testing stage, it can be concluded that IMU sensor on APM 2.5 has a better accuracy than 3 Space YEI sensor.

The second phase was cross-axis effect testing on IMU sensor. Cross-axis effect on IMU sensor was the change in the value of an angle (axis 1) when the value of the other angle (axis 2) changes when the tilt angle orientation axis 1 are likely to remain. Cross axis effect caused readings on an axis influenced the readings on other axis. Testing methods performed the same as in the previous test, except that on the stage of testing the value of the three sensors directly recorded at the same time. In this test, there was a variable axis and a constant axis. In variable axis, the axis tilt angle was made arbitrarily. While constant axis was the axis that is expected to have a constant value, although the value of a variable axis changes.

Table 2
RMS error of cross axis effect testing on YEI 3 Space sensor

| | *Roll RMS error* | *Pitch RMS error* | *Yaw RMS error* |
|---|---|---|---|
| yaw variable | $5{,}31^o$ | $1{,}12^o$ | - |
| pitch variable | $1{,}29^o$ | - | $7{,}4^o$ |
| roll variable | - | $0{,}72^o$ | $2{,}94^o$ |

Table 3
*RMS error of* cross axis effect testing on *IMU* sensor of APM 2.5

| | *Roll RMS error* | *Pitch RMS error* | *Yaw RMS error* |
|---|---|---|---|
| yaw variable | $0{,}54^o$ | $1{,}02^o$ | - |
| pitch variable | $2{,}00^o$ | - | 1,87 |
| roll variable | - | $2{,}06^o$ | $5{,}89^o$ |

Cross axis effect was caused by error mixing algorithm of data (sensor fusion) of the sensors that make up the IMU (accelerometer, gyroscope, and magnetometer). Moreover, it can be caused by the sensor accelerometer, gyroscope, and magnetometer that are not symmetrical with a package of sensors. RMS error of the data contained in Table 4.10 and 4:11 can be concluded that cross axis effect occurs equally in both sensors were tested. Cross-axis effect produces significant RMS error on a particular axis like a pair relations between the roll and yaw axis readings on both sensors produce RMS error more than $5^o$.

The last test IMU sensor was noise endurance test in Quadrotor environment. This test was done by putting sensors on the IMU Quadrotor framework. This testing needs to be done to determine how reliable the IMU when placed on the quadrotor environment because there is a lot of noise caused by vibration from the motor which will affect the sensor readings.

This test method is done by putting the two sensors on the Quadrotor in two different conditions. In the first condition, the motor of Quadrotor totally turned on then the sensor readings displayed in graphs on the computer. In the second condition, the four motors of Quadrotor given speed by 30% then the readings from sensor was displayed in computer as a graph. At this speed, quadrotor still cannot fly so that the sensor readings should be in a stable condition.

Especially for YEI 3 Space accelerometer sensor has an adjustable confidence features. The higher confidence value of the accelerometer, the more sensor fusion algorithm tend to use data from accelerometer rather than the data from the gyroscope. From the test results, the higher the value of accelerometer confidence, the smaller RMS error sensor readings on the axis of pitch, roll, and yaw. Best results obtained when accelerometer confidence rated 500. RMS error comparison between the two sensors is presented in the following table. RMS error on YEI 3 Space accelerometer sensor confidence taken when rated at 500.

Table 4
RMS error of IMU sensor measurements in quadrotor environment

| *Sensor* | *Pitch RMS Error* | *Roll RMS Error* | *Yaw RMS Error* |
|---|---|---|---|
| APM 2.5 | $0{,}16^{o}$ | $0{,}164^{o}$ | $0{,}077^{o}$ |
| YEI 3 Space (accelerometer confidence = 500 | $1{,}94^{o}$ | $3{,}48^{o}$ | $2{,}46^{o}$ |

From the third phase of this test, it can be concluded that IMU sensor on APM 2.5 has a better measurement than YEI 3 Space sensors because IMU sensor of APM 2.5 has smaller RMS error. APM 2.5 also has smaller cross axis effect. In addition, APM 2.5 was more resistant to environmental noise when placed in quadrotor.

## B. Controller Test

Controller test had three stages. The stages were test of roll pitch control, yaw control, and altitude control. The controller test was conducted to get the proper value for the parameter of PID control when hovering at a height of 15 cm.

Pitch and roll controller test performed on a pair of opposing motors. When the controller test was performed in pitch axis , the red and yellow motor speed was controlled while the green and blue motor were not turned on. The speed difference between the two motors (red and yellow) will cause the pitch angle deviation of quadrotor.

Because it's only uses two motors in this test, the Quadrotor cannot fly. To get the proper PID tuning at a height of 15 cm, then the quadrotor was tied up to the cantilever so that the arm of quadrotor that connect yellow and red motor can move freely at a height of 15 cm which was the desired hovering altitude. The cantilever that attached to the framework of quadrotor was not impede the movement in the pitch axis.

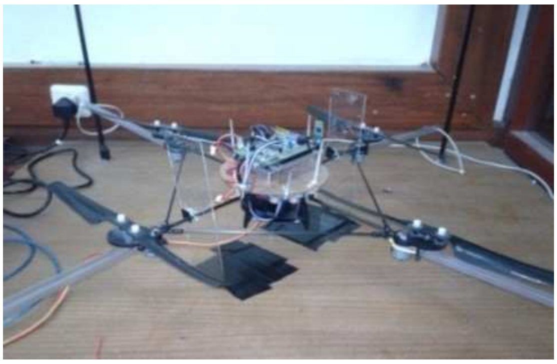

Figure 8. Quadrotor was tied up to the cantilever on controller test

Controller test in roll axis also used the same method to test pitch controller. However, in this test, the controller controlled the speed of blue and green motor, while the red and yellow motor were turned off. PID tuning was performed at each angular position. The target was capable of producing a stable pitch and roll at $0^{o}$. When the disruption of the deviation angle was given to the system, the controller was able to make improvements to return to the set point as shown in the picture below. The third kind of PID controller which was used in the test was capable of stabilizing the pitch and roll axis position. When the disturbance was given, the third PID controller mode tend to have a faster recovery time.

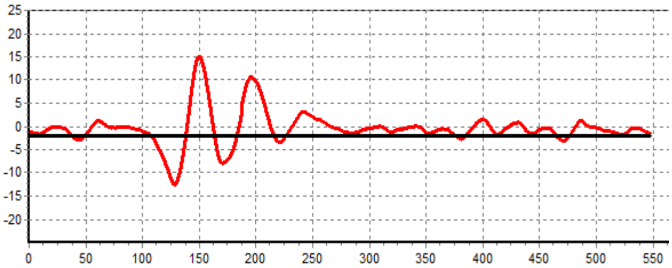


Figure 9. The graph of pitch angle vs time using PID mode 1 with Kp = 0.12 and Kd = 0.03

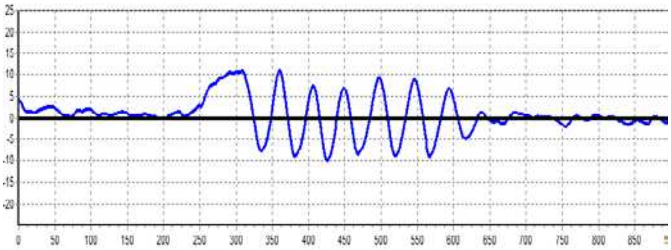

Figure 10 The graph of roll angle vs time using PID mode 2 with Kp = 0.14, Kd = 0.8, and Ki = 0.003

Yaw controller test was performed on the floor without using cantilever so quadrotor can move freely. But in this test, the basic speed was below 50% so quadrotor didn't float above the floor.

Figure 11. Yaw controller test

Yaw axis control used PID mode 1. The controller set point was the value of the yaw sensor reading in the first time (initial value). Set point value was $90^o$. PID controllers were able to restore the position of heading when a disturbance or deviation angle was given to quadrotor as shown in Figure 12.

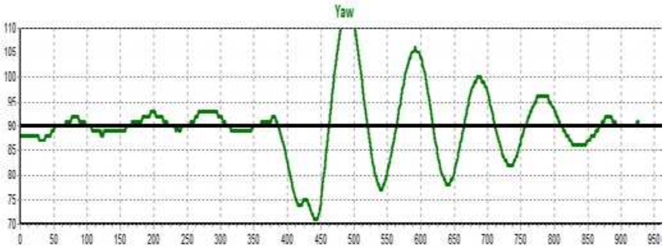


Figure 12. Yaw PID controller test

The last test was quadrotor free hovering. But in this test, each of the end of the quadrotor arm tied on cantilever to protect Quadrotor when an error occurs in the control process. However, this cantilever did not interfere the motion of the quadrotor.

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Table 5
RMS error attitude and altitude while hovering at 15 cm

| PID Controller | pitch RMS error | roll RMS error | yaw RMS error | altitude RMS error | Stability |
|---|---|---|---|---|---|
| Mode 1 | $5.4^o$ | $4.3^o$ | $30^o$ | 5 cm | Unstable |
| Mode 1 | $6.2^o$ | $7^o$ | $35^o$ | 5.2 cm | Unstable |
| Mode 1 | $5.3^o$ | $6.4^o$ | $45^o$ | 4.5 cm | Unstable |
| Mode 3 | $3.4^o$ | $4.3^o$ | $24^o$ | 2.6 cm | Stable |
| Mode 3 | $2.5^o$ | $3.6^o$ | $25^o$ | 3 cm | Stable |

Figure 13. Free hovering quadrotor test

The results show that the simple PID controller (mode 1) was not able to make a stable attitude during the quadrotor hovering process. Alternative PID controller with filtered derivative action (mode 3) was able to stabilize the current Quadrotor hovering in control process but there are still drifting effect.

## IV. CONCLUSION

The RMS error of IMU sensor on Ardupilot Mega (APM) 2.5 was less than $1^o$ while RMS error on YEI 3 Space more than $1^o$ when used in quadrotor environments. Therefore IMU sensor on APM 2.5 was more suitable to be used as an IMU sensor on Quadrotor.

Simple PID controller could not control the stability of quadrotor attitude when it hovered at a height of 15 cm. RMS error on roll and pitch axis was more than $5^o$. While the PID controller with filtered derivative action could stabilize quadrotor hovering process (pitch and roll RMS error was less than $5^o$) but drifting occurs during the process so that each of the end of the quadrotor arm was tied to the cantilever to keep it out of bounds testing spot.

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