Development of a Low-Cost Embedded Flight Controller for Quadcopter

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***Abstract*—Quadcopter has been interesting researchers due to its wide application, such as surveillance, mapping, delivery drone, *etc*... Developing a low-cost embedded flight controller unit (EFCU) for making the quadcopter autonomous is still challenging problem. In this work, an EFCU is developed based on ARM STM32F103C8T6 microcontroller, the MPU6050 IMU sensor and the HC-SR04 ultrasonic sensor. An PID control strategy is implemented for automatically take-off, landing, and stabilizing control of the quadcopter. The EFCU and PID controller is developed in this work. It is implemented and tested experimentally by providing error on roll and pitch position in 0.71° and 0.68°, respectively.**

Keywords—quadcopter, low-cost embedded flight controller, PID controller, autonomous flight controller

I. Introduction

The Unmanned Arial Vehicle (UAV) or drone is an aerial vehicle without a pilot on it. There is a system for the UAV called the Unmanned Aerial System (UAS) that allows communication with the physical drone [1]. Drones are often controlled by a human pilot by using a remote control that is known as Radio Controller (RC). On the other hand, it can be autonomously controlled by the system integrated on the drones themselves without using the RC input. The UAS is installed on the companion computer which is called onboard computer [2][3]. The drone was initially developed for a military purpose, had its test flight before the World War II, and then was fully deployed in the Iraq War and the Afghan War around 2000 [4].

Nowadays, UAS has been developed and applied not only in military purpose. Quadcopter, also known as quadrotor as one variant of UAS, is a helicopter with four rotors and simple structure. The quadcopter is controlled by adjusting the angular velocity of the rotors which are spun by electric motors. Quadcopter has received considerable attention from researchers due to its simplicity and wide applications such as surveillance, search and rescue, construction inspections, *etc*..[5-7]

Research on making the quadcopter take-off/landing automatically is interested many researchers. A low-cost vision-based autonomous quadcopter was proposed in some works [8-11]. However, the drawback of using vision is the latency in computational process. It needs relative longer time for obtaining an information as feedback of controller. Since the quadcopter is a very dynamics system which is normally unstable, it needs relatively high-speed feedback system. Therefore, IMU sensor is still the best choice for stabilization feedback. To build a low-cost quadcopter, a low-cost controller unit is also needed. In the previous work, an energy efficient controller was proposed [12]. Unfortunately, the controller is implemented in a PC-based quadcopter testbed. However, it is important to test the algorithm in a real autonomous quadcopter that is controlled with an embedded controller.

In commercially, there are many low-cost quadcopters. Unfortunately, we will find difficulty to extend or customize its function due to the design of the embedded controller is closed by the manufacturer. Therefore, the purpose of this paper is to present the basics development of a low-cost embedded controller unit of a quadcopter that has capability in stabilization and automatically take-off and landing. The challenge in controlling a quadcopter is that the quadcopter has six degrees of freedom but there are only four control inputs and therefore it is considered as an underactuated system. The embedded controller build in this work is based on STM32F103C8T6 microcontroller. A PID controller is designed for stabilizing the attitude and altitude position. The trajectory is designed as set points of altitude control to make it can take-off autonomously. In this research, "x" configuration quadcopter is selected instead of "+" configuration due to its advantage in better force distribution [13], as shown in Fig. 1.

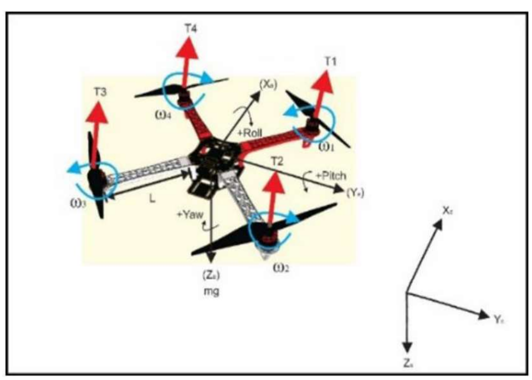


Fig. 1 Force distribution and X configuration

II. SYSTEM DESIGN

In this work, a preliminary design of quadcopter Embedded Flight Controller Unit (EFCU) including a conventional PID for stabilization is presented. The EFCU controls the quadcopter in hovering/altitude hold mode and automatic take-off and landing. The ultrasonic sensor HC-SR04 is used for measuring the altitude of quadcopter while hovering. Whereas, to measure translation (X,Y,Z) and rotation (Roll, Pitch, Yaw) movement of quadcopter in each DoF, the Inertia Measurement Unit (IMU) MPU6050 is chosen.

A. Embedded Flight Controller Unit (EFCU)

The embedded processor used on the EFCU is STM32F103C8T6 made by ST Micro-electronic. It is a 32 bit microcontroller with core ARM Cortex-M3. It can work in frequency up to 72 MHz. The block diagram of EFCU is shown in Fig.2, which is consist of 3 blocks: input, process, and output.

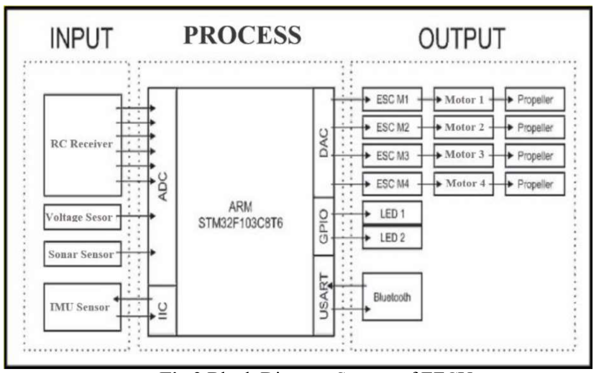


Fig.2 Block Diagram System of EFCU

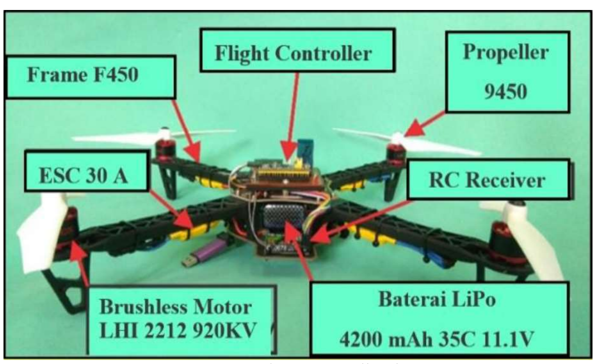


Fig. 3 Quadcopter Realization

There are 4 input source connected to the main controller: receiver RC with 6 channel remote control for giving trajectory data, voltage sensor providing battery voltage of battery information, ultrasonic sensor HC-SR04 for altitude sensor, and IMU sensor MPU6050 that providing acceleration data in 3 axis (X,Y,Z) and angular velocity in 3 axis. IMU can communicate with main processor using I2C communication. Furthermore, the output part consists of: 4 ESCs for controlling rotation of 4 motors and its propellers; 2 LEDs as indicators; and serial communication using Bluetooth HC05 for monitoring data of quadcopter in PC while flight testing. Figure 3 shows the realization of the quadcopter with the EFCU. The detail part of EFCU is shown in Fig. 4.

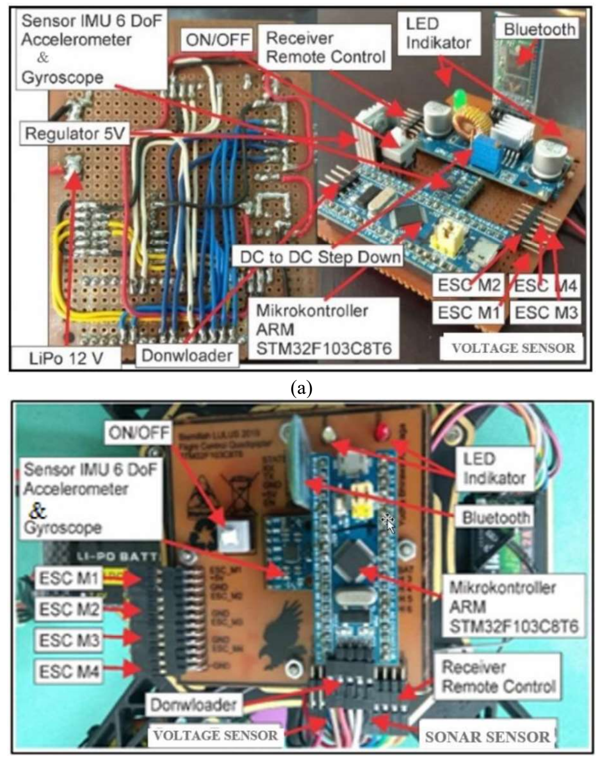
B. IMU signal processing

In stabilization of the quadcopter, the IMU sensor MPU6050 that has 3 DoF accelerometer, 3 DoF gyroscope and temperature sensor, is utilized. The rotational position is calculated by these 6 DoF sensor using fusion method. First, roll (Φ_g), pitch (θ_g) and yaw (Ψ_g) positions are obtained by integrating angular velocity resulting from gyroscope sensor as follows:

$$\Phi_g(t) = \int_0^t \dot{\Phi}_g\,(t)dt \qquad (1)$$

$$\theta_g(t) = \int_0^t \dot{\theta}_g\,(t)dt \qquad (2)$$

$$\Psi_g(t) = \int_0^t \dot{\Psi}_g\,(t)dt \qquad (3)$$



(a)

(b)

Fig. 4 Flight Controller Quadcopter: (a) Prototype, (b) Board

The gyroscope sensor is quite poor in measuring the angular position by using the integral function due to error measurement accumulation, especially in low frequency motion. Therefore, we use the accelerometer sensor to correct the error measurement from gyroscope by utilizing vector of acceleration in 3-axis (x, y, z). Unfortunately, only roll and pitch positions can be corrected by accelerometer because these motions are related to the gravitational acceleration. Accelerations in each axis (a_x, a_y, a_z) are obtained from 3 DoF accelerometer sensor. The roll (Φ_a) and pitch (θ_a) are calculated as follows:

$$\Phi_a = sin^{-1}\left(\frac{a_x}{|A|}\right) \qquad (4)$$

$$\theta_a = sin^{-1}\left(\frac{a_y}{|A|}\right) \qquad (5)$$

where $|A| = \sqrt{a_x{}^2 + a_y{}^2 + a_z{}^2}$

However, the accelerometer is effective in measuring the angular position in low frequency motion. Furthermore, for calculating the roll (Φ) and pitch (θ) of the quadcopter, we fusion these resulting measurements by using complementary filter [14], as shown in Fig. 5.

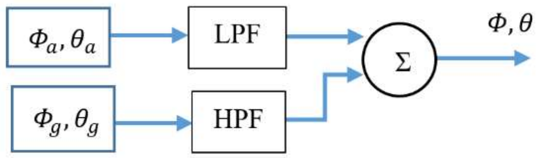


Fig. 5 Complementary filter

where:

LPF $= \frac{1}{1+\alpha.s}$; HPF $= \frac{\alpha.s}{1+\alpha.s}$; α is cut-off frequency.

C. Altitude Sensor

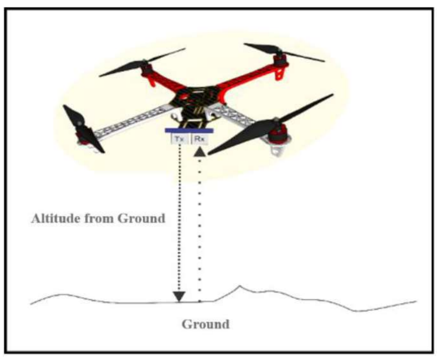


Fig. 6 Ilustration reading altitude of quadcopter

Altitude of quadcopter to ground can be obtained using ultrasonic sensor HC-SR04. This sensor works as follows : transmitter (Tx) sends ultrasonic wave in velocity *v*, then travelling time (in second) of ultrasonic wave from transmitter to receiver (Rx) is measured to know altitude of quadcopter. It is formulated as follow:

Altitude= (Time tracking * 0.5) * 340

D. Design Control System

Quadcopter motion is produced by controlling the speed of all 4 propellers ($\omega_1, \omega_2, \omega_3$, and ω_4) that produce forces as shown in Fig. 1. Speed of each propeller is controlled by controlling the value of PWM that fed to each ESC (electronic speed controller).

For stabilzing the quadcopter and automatic take-off controller, the cascade PID controller is applied. The control structure is shown in Fig. 7. The formula for each PID controller is as follow:

$$PID(t) = K_p * e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{6}$$

$e(t)$ is corresponding error, K_p, K_i, and K_d are control parameters for proposional, integral and diferensial control, respectively.

Furthermore, the output of each PID controller is coverted into PWM for each ESC by using tranformation matrix as follow:

$$\begin{bmatrix} PWMesc_1 \\ PWMesc_2 \\ PWMesc_3 \\ PWMesc_4 \end{bmatrix} = \begin{bmatrix} -k & k & -k & k \\ -k & -k & k & k \\ k & -k & -k & k \\ k & k & k & k \end{bmatrix} \begin{bmatrix} PID\dot{\Phi} \\ PID\dot{\theta} \\ PID\dot{\Psi} \\ PIDz \end{bmatrix} \tag{7}$$

where *k* is positive constant.

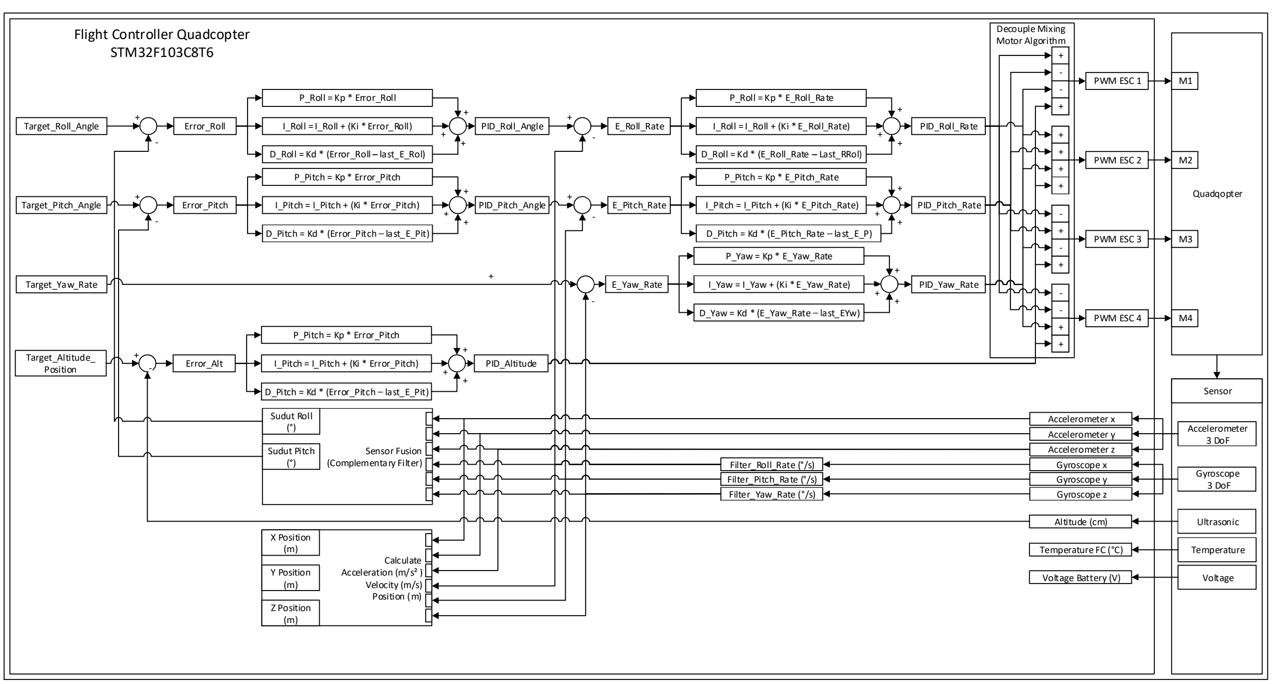


Fig. 7 Control structure for stabilizing the quadcopter

III. EXPERIMENTAL RESULTS AND DISCUSSION

The all algorithm of EFCU is developed in Arduino. The PID parameters are obtained tuning intuitively. The values of all parameters are given in Table.1. For *k* and α are chosen as 1500/9.8 and 0.9996, respectively. The sampling period is set on 4 ms (250 Hz). The Experimental condition is shown in Fig. 8.

Fig. 8. Experimental condition

Table 1 Constant Parameter PID

No	PID Control System	Constant Parameter PID		
		Kp	**Ki**	**Kd**
1	Roll Angular	5.000	0.000	0.000
2	Roll Angular velocity	1.700	0.001	8.000
3	Angular Pitch	5.000	0.000	0.000
4	Pitch Angular velocity	1.700	0.001	8.000
5	Yaw Angular velocity	4.000	0.020	5.000
6	Altitude	1.500	0.000	0.000

In experiments, the performance of the EFCU is evaluated. Since the ultrasonics sensor is used for measuring the altitude, we have limitation in altituted position. The scenario of experiment is, first the quadcopter take-off, then hovering in certain altitude, and finally the quadcopter landing automatically. Performance in altitude control is shown in Fig. 9. It is seen that the EFCU is succes to fly the quadcopter automatically. However, in this trial, the trajectory for take-off is designed as a step function and the respons of quadcopter produce an overshoot. We redesign the trajectory for take-off into a multi-step input. This scenario succes to reduce the overshoot as shown in Fig. 10.

In stabilizing the attitude position, the EFCU also success to control attitude of quadcopter as shown in Fig. 11. The average error in roll and pitch position are 0.81° and 0.58°, respectively. To show consistency of the EFCU, several experiments are performed and the results are shown in Fig. 12. In average, root mean square error (RSME) off attitute position on roll and pitch are 0.71° and 0.68°, respectively. The standard deviation on roll and pitch are not more then 0.7° and 1°, respectively.

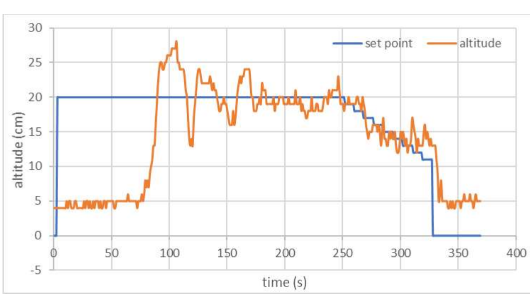


Fig. 9. Altitude control experiment

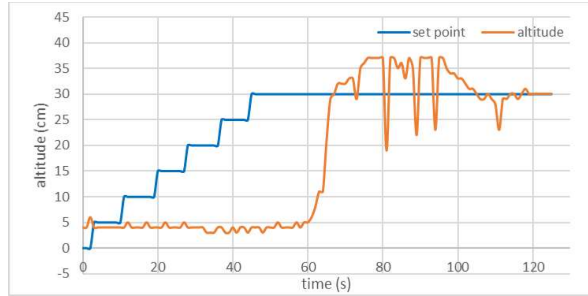
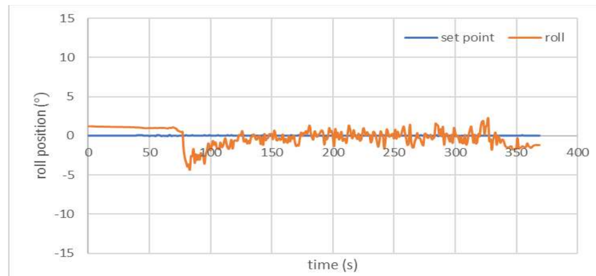
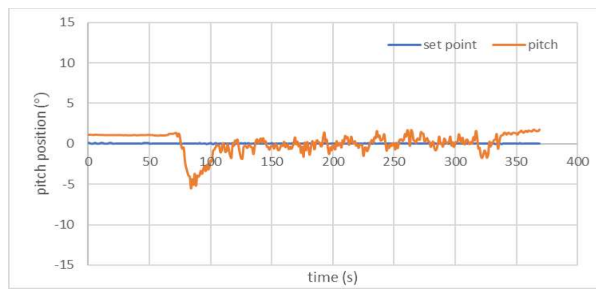


Fig. 10. Multi-step input for automatic take-off

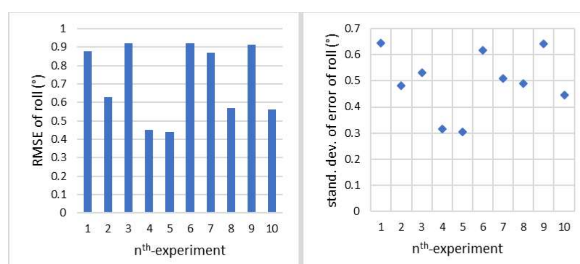


(a)



(b)

Fig. 11. Attitude position of quadcopter: (a) Roll; (b) pitch



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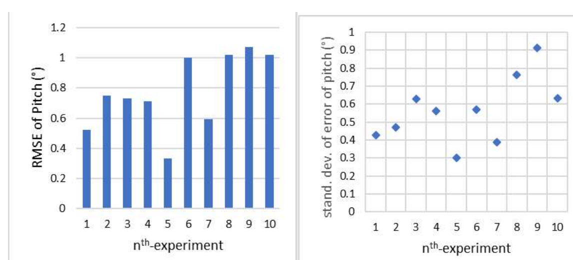
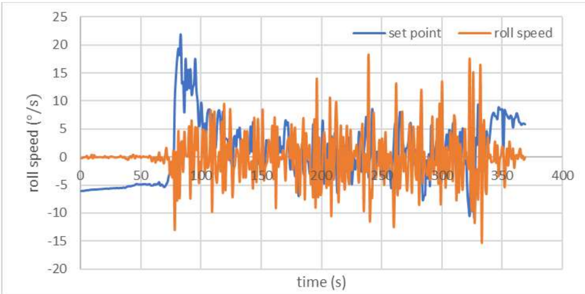


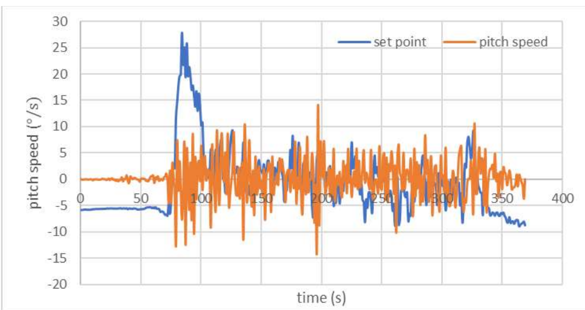
(b)

Fig. 12 RSME and standard deviation of error on attitude position: (a) roll; (b) pitch

In controlling the angular speed, as inner loop in control structure, the EFCU also success to controll the quadcopter. The experimental results are shown in Fig. 13. The set points of roll and pitch speed are produced by the outer loop controller, as roll and pitch position control loop.



(a)



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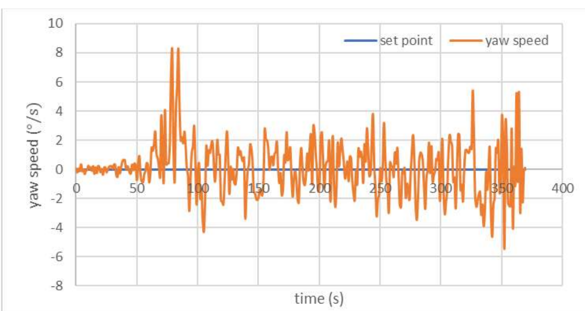

(c)

Fig. 13 Angular speed of quadcopter

In this preliminary result, the EFCU only control roll and pitch position for the attitude while in yaw position is not controlled yet, only yaw speed is controlled. This is due to the drawback of IMU sensor that is not utilized magnetometer sensor. In future work, we will consider magnetometer sensor for correcting the yaw position.

Profile of PWM sent to each ESC, as output of control strategy, is shown in Fig. 14. In hovering, the PWM sent to ESC is about 1500. However, the value of PWM in hovering ideally should be equal for all motors. The different shown in Fig. 14 is due to the unbalance of mechanical system.

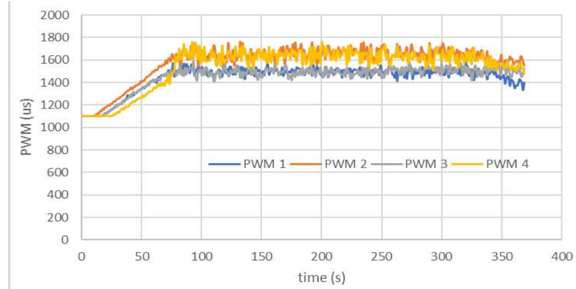

Fig. 14 Profile of PWM on each ESC

The other consideration in quadcopter system is availability of power source that is provided by battery. In this work, the specification of used battery is 4200mAh 35C with nominal voltage 11.1 Volt. Profile of battery voltage during experiment is shown in Fig. 15. It seen that the battery voltage is drop almost 1 volt during flying of quadcopter. This issue, power consumption, could be other consideration for future research.

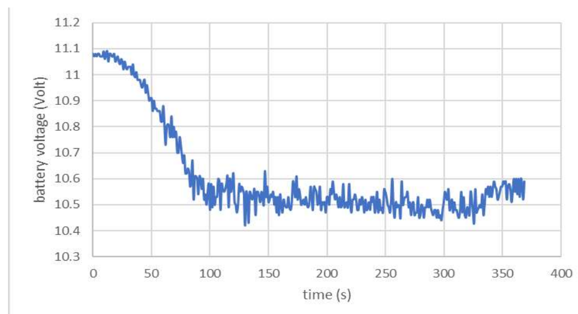

Fig. 15 Profile of battery voltage during experiment

IV. CONCOLUSION

In this research a quadcopter embedded flight controller unit (EFCU) has been made based on the ARM STM32F103C8T6 microcontroller, the MPU6050 IMU sensor and the HC-SR04 ultrasonic sensor. An automatic control based on PID method is implemented for controlling the quadcopter in take-off, hovering, and landing. The EFCU success to automatically control the motion of quadcopter by following the given trajectories. However, there are some drawback should be considered in the future work, such as correction of yaw position feedback and power consumption.

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