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Low-cost quadrotor hardware design with PID control system as flight controller

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Abstract

In designing an Unmanned Aerial Vehicle (UAV), such as quadrotor, sometimes an engineer should consider the required cost that is relatively expensive. As we know, quadrotor is one of robots that very usefull and has several advantages for human needs such as disaster area monitoring, air quality monitoring, area mapping, aerial photography, and surveillance. Thus, designing a rapid quadrotor with low-cost components and simple control system needs to be considered here. This paper presents design and implementation of a quadrotor using relatively low-cost components with Proportional Integral Derivative (PID) control system as its controller. The components used consist of microcontroller, Inertial Measurement Unit (IMU) sensor, Brushless Direct Current (BLDC) motor, Electronic Speed Control (ESC), remote control unit, battery, and frame. These components can be easily found in the electronic markets, especially in Indonesia. As an addition, this paper also describes PID control system as flight controller. A simple economic analysis is presented to clarify the cost in designing this quadrotor. Based on experimental testing result, the quadrotor able to fly stably with PID controller although there still overshoot at the attitude responses.

Keywords*: control, hardware, low-cost, PID, quadrotor*

1. Introduction

Unmanned Aerial Vehicle (UAV) is a flying vehicle that can operate with the remote control by the pilot or able to control itself that uses aerodynamic laws. UAV is widely used due to have several advantages if compared with manned aerial vehicle. Recently, there are two types of UAV based on its actuator which are fixed-wing UAV and multirotor UAV. Fixed-wing UAV utilizes the aerodynamic forces in order to fly, while multirotor UAV uses more than one rotor. Multirotor UAV that has four rotors is called a quadrotor. Quadrotor has several uses, especially for disaster area survey [1], air quality monitoring [2], earth area mapping [3], and CBRN (Chemical, Biological, Radioactive, and Nuclear) area mapping [4].

In designing a quadrotor, cost is one of the things that should be considered by an engineer. Some quadrotor hardwares are available in the market and sometimes we are faced with some relatively expensive prices. In other words, the goal that needs to be achieved in building a quadrotor is the low-cost component and good control system. Low-cost quadrotor designs have been presented previously, such as Microraptor that was developed by Oakland University with the total cost used is 3000 USD [5]. Other UAV quadrotors, named VORTEX has also been developed with cost of 450 EUR [6]. The commercial quadrotor also has used as a low-cost platform for research named AR.Drone with price about 300 USD [7, 8].

In another side, to control the quadrotor, the controller may have to be designed as simple as possibles. Several quadrotors have been designed with various controllers in last few years such as Proportional-Integral-Derivative (PID) controller [9-12], Fuzzy Logic Control (FLC) [13-15], Linear Quadratic Regulator (LQR) [16], and robust controller [17]. However, PID controller is mostly control method which many used on UAV, especially quadrotor. This controller is used due to the simplicity in terms of design implementation. Quadrotor with PID controller can be modeled using MATLAB/Simulink and it useful for quadrotor researches [18, 19]. PID controller also has better performance if compared with Linear Quadratic (LQ) controller since used for indoor quadrotor [20] although it is not more robust compared to FLC [21]. Lastly, Proportional Derivative Active Force Control (PDAFC) is

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employed for “x” configuration quadrotor to stabilize and reject disturbance uncertainty by estimating disturbance torque value [22].

In contrast with the previous research, this study aims to design a relatively low-cost quadrotor and implement it with PID controller as flight control system. The quadrotor is assembled using low-cost components in “x” configuration. This configuration is more stable if compared with “+” quadrotor configuration [23]. Components used in this study can be obtained in the market easily, either online and offline. As a flight controller, PID control system is implemented to control the third attitudes of quadrotor by using simple and rapid designs [24]. PID controller is very suitable for this case due to the simplicity in terms of design and implementation.

2. Research Method

In this study, design methodology of quadrotor and PID controller includes modeling quadrotor dynamic, hardware design, control system design, and programming algorithm.

2.1. Quadrotor Dynamic

A dynamic model of quadrotor type “x” is used in this study as depicted in Figure 1. The model consists of earth coordinate frame and quadrotor body frame. In the earth coordinate frame, there exist quadrotor attitudes which are the roll (θ), pitch (φ), and yaw (ψ). Angular velocities (ω) and vertical forces (f) are variables in the body frame that produces the torque.

2.2. PID Controller Design

PID controller is linear control system method which consists of three terms controller type which are proportional, integral, and derivative. Each controller has different task in improving the dynamic response of controlled plant. Generally, the structure of PID controller is shown in Figure 2. The detailed explanation is described as follows [25].

a. Proportional

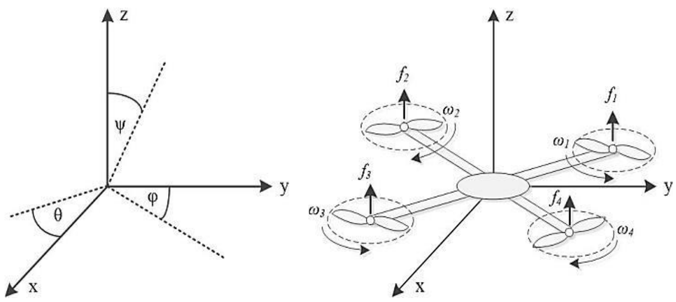
Proportional controller works by multiplying error value with proportional constant Kp. The larger Kp value my cause instability of the system, when the smaller Kp value may cause the system drift away.

b. Integral

Integral controller works by integrating error value and multiplied by an integral constant Ki. In other words, integral controller is able to eliminate error steady state. The larger Ki value may produce oscillation in dynamic response and the smaller Ki value may result in a sluggish response

c. Derivative

Derivative error value is multiplied by a derivative constant Kd. Similarly with the integral controller, if the Kd is too large the system may oscillate and if the Kd is too small the response may be sluggish.



(a) (b)

Figure 1. Dynamic structure of quadrotor: (a) earth coordinate frame and (b) body frame

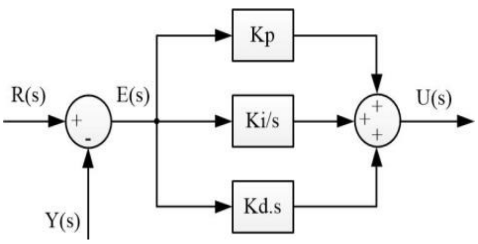


Figure 2. PID controller structure

Referring PID controller structure, the control signal is derived in continuous and discrete times as (1) and (2).

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

$$u(kT) = K_p e(kT) + K_i T \sum_{k=1}^{n} e(kT) + K_d \frac{e(kT)-e(kT-T)}{T} \quad (2)$$

where u is control signal, e is error value, t and kT respectively are continuous and discrete time forms.

According to the description above, PID controller may be used to enhance the dynamic response of quadrotor. Combination of PID constant value needs to be considered because it determines the controlling result. When a PID controller is used, it is important to tune the controller constants to achieve the required response. Tuning a PID controller involves selecting values for the controller constants Kp, Ki, and Kd. Some tunning method can be used such as trial-error and Ziegler-Nichols. The optimization methods are also developed to obtain the optimal value of PID constants i.e fuzzy logic, genetic algorithm, and particle swarm optimization. However, these methods are required when the controller is designed in analysis approach and robustly. In this paper, we obtain the PID constants from the literature study in order to give a rapid way to design PID controller. Block diagram of control system is then designed as depicted in Figure 3.

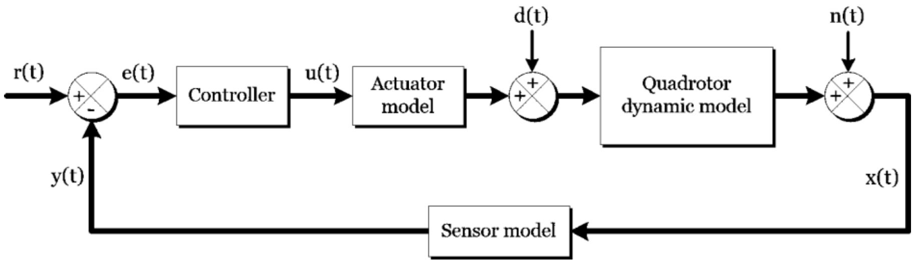


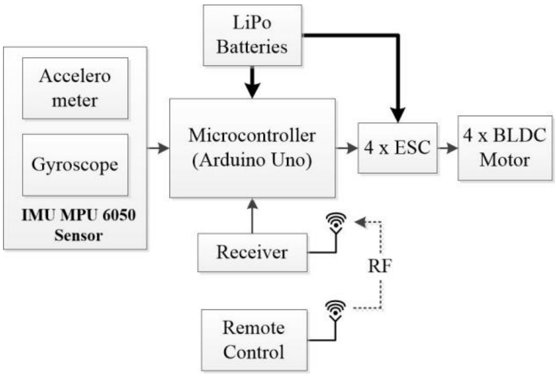
Figure 3. Quadrotor control system design

Block diagram of control system consists of quadrotor plant, sensor, controller, and actuator. Quadrotor plant can be constructed with including disturbance and noise signal. The sensor is used to measure attitude movement of the quadrotor. The controller is available to stabilize the attitude when there is an error in the sensor measurement. The actuator will receive control signal from the controller so that the control process can be conducted. The controller provides PID constants which are used to control third quadrotor attitudes. Thus, there are 9 constants in this design. Based on this consideration, following (3) explains the PID controller design in the discrete time domain which is then converted to motor voltages.

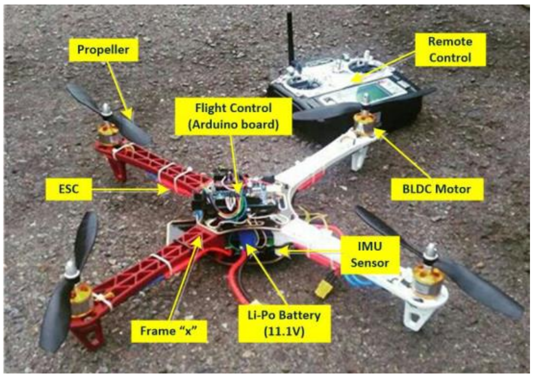
$$\begin{bmatrix} u_\theta(kT) \\ u_\phi(kT) \\ u_\psi(kT) \end{bmatrix} = \begin{bmatrix} Kp_\theta e_\theta(kT) + Ki_\theta T \sum_{k=1}^{n} e_\theta(kT) + Kd_\theta \frac{e_\theta(kT)-e_\theta(kT-T)}{T} \\ Kp_\phi e_\phi(kT) + Ki_\phi T \sum_{k=1}^{n} e_\phi(kT) + Kd_\phi \frac{e_\phi(kT)-e_\phi(kT-T)}{T} \\ Kp_\psi e_\psi(kT) + Ki_\psi T \sum_{k=1}^{n} e_\psi(kT) + Kd_\psi \frac{e_\psi(kT)-e_\psi(kT-T)}{T} \end{bmatrix} \quad (3)$$

2.3. Hardware Design

In this study, the quadrotor is assembled using relatively low-cost components which are microcontroller, IMU sensor, BLDC motor, ESC, remote control unit, battery, and frame. These components are integrated become a quadrotor hardware which has the total weight of 3.85 Kg. The microcontroller used is ATMega 328p with clock speed 16 MHz that integrated on Arduino Uno board. We use MPU-6050 IMU sensor with 6 degrees of freedom (DOF) that is a combination of Gyroscope and Accelerometer. Four units of A2212 BLDC motor 1000 KV is also used as the actuator combined with 4 units of propeller with radius 4.5 inch and Simonk ESC 30 A as a speed controller. Flysky FS-i6 remote control with radio frequency 2.4 GHz is communicated with its receiver on quadrotor hardware as a pilot controller. We use 3 cell Lithium-Polymer (LiPo) batteries which have a voltage of 3.7 V in each cell. Lastly, the frame used has "x" configuration with the length of each arm is 0.21 m. Those components above is configured and assembled become a quadrotor hardware as shown in Figure 4.



(a)



(b)

Figure 4. Quadrotor hardware: (a) design and (b) implementation

2.4. Programming Algorithm

In designing a quadrotor, we also need to design software algorithm that formed in programming language and embedded on the microcontroller. In this study, we use Arduino IDE as a compiler with C/C++ programming language. The overall programming structure including PID algorithm on microcontroller as flight controller is depicted as Figure 5.

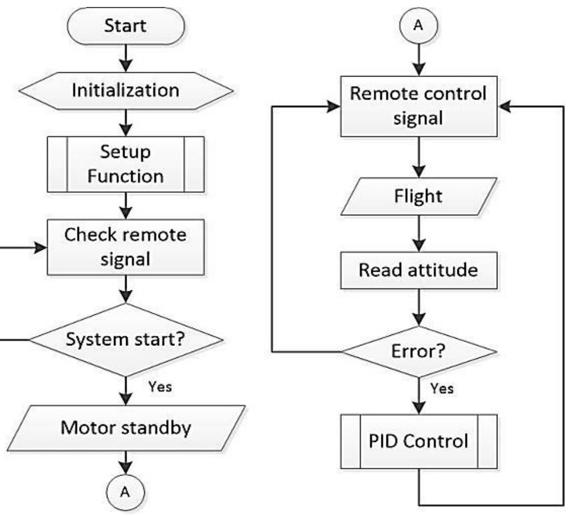


Figure 5. Programming structure on microcontroller

PID controller designed previously is also formed into programming language according to (2) as follows:

```
//Calculate PID roll
pid_output_roll = pid_p_gain_roll * pid_error_temp + pid_i_mem_roll +
pid_d_gain_roll * (pid_error_temp - pid_last_roll_d_error);
if(pid_output_roll > pid_max_roll)
       pid_output_roll = pid_max_roll;
```

```
else if(pid_output_roll < pid_max_roll * -1)
      pid_output_roll = pid_max_roll * -1;
else pid_last_roll_d_error = pid_error_temp;

//Calculate PID pitch
pid_output_pitch = pid_p_gain_pitch * pid_error_temp + pid_i_mem_pitch +
pid_d_gain_pitch * (pid_error_temp - pid_last_pitch_d_error);
if(pid_output_pitch > pid_max_pitch)
      pid_output_pitch = pid_max_pitch;
else if(pid_output_pitch < pid_max_pitch * -1)
      pid_output_pitch = pid_max_pitch * -1;
else pid_last_pitch_d_error = pid_error_temp;

//Calculate PID yaw
pid_output_yaw = pid_p_gain_yaw * pid_error_temp + pid_i_mem_yaw +
pid_d_gain_yaw * (pid_error_temp - pid_last_yaw_d_error);
if(pid_output_yaw > pid_max_yaw)
      pid_output_yaw = pid_max_yaw;
else if(pid_output_yaw < pid_max_yaw * -1)
      pid_output_yaw = pid_max_yaw * -1;
else pid_last_yaw_d_error = pid_error_temp;
```

3. Results and Analysis

3.1. Price Analysis

The detail cost used in this study can be seen in Table 1. Based on these details, the total cost required in designing this quadrotor is 2,168,000 IDR or around of 150 USD. This cost can be said to be relatively low-cost if compared to the price of a commercial quadrotor that can reach 20,000,000 IDR or other low-cost quadrotors that have been designed previously. This assembled quadrotor also has advantages in terms of its development. This quadrotor can be developed again as well as hardware and control system in accordance with its utilization.

Table 1. Detailed Prices of Quadrotor Component

Components	Quantity	Unit Price (IDR)	Total (IDR)
Arduino Uno microcontroller board	1	370,000	370,000
IMU MPU-6050 sensor	1	30,000	30,000
BLDC motor A2212 1000 RPM/V	4	50,000	200,000
ESC Simonk 30A	4	70,000	280,000
Remote Control FlySky FS-i6 + Receiver	1	769,000	769,000
Li-Po Battery 2200 mAh	1	280,000	280,000
Frame F450	1	159,000	159,000
Propeller radius 0.11	4	20,000	80,000

3.2. Hardware Testing

Hardware testing is done to ensure that the component works properly. In this study, the tests are performed on IMU sensor, remote control, and propeller. IMU sensor testing is done by giving attitude input and observes the output value generated through serial communication. There are 6 attitudes tested: positive roll, negative roll, positive pitch, negative pitch, positive yaw, and negative yaw. The test results shown in Figure 6 show that the IMU sensor works well even if there is noise. Remote control testing is done by giving attitude commands and observing the digital data received by the microcontroller. The test results are shown in Figure 7 for digital data and change in throttle value when given a command by the pilot. Based on the test results, it can be obtained that the remote control can work well and can give command to the quadrotor. Then, propeller testing is performed to balance the propeller precision. Designed flight control system will not work properly if the used propellers are unbalanced. The test is performed using a propeller balancing tool and adjusted by adding a small amount of material to the propeller such as a paper patch. The result is shown in Figure 8 where there is a different noise signal produced by the quadrotor sensor readings before and after the balancing process.

3.3. Controller Testing

After designing PID controller and the quadrotor, then we do the testing to know the performance. PID constants used in this study can be seen in Table 2. There are 9 constants to control roll, pitch, and yaw attitude of quadrotor. These constants are obtained from literature study and have adjusted previously using trial and error method.

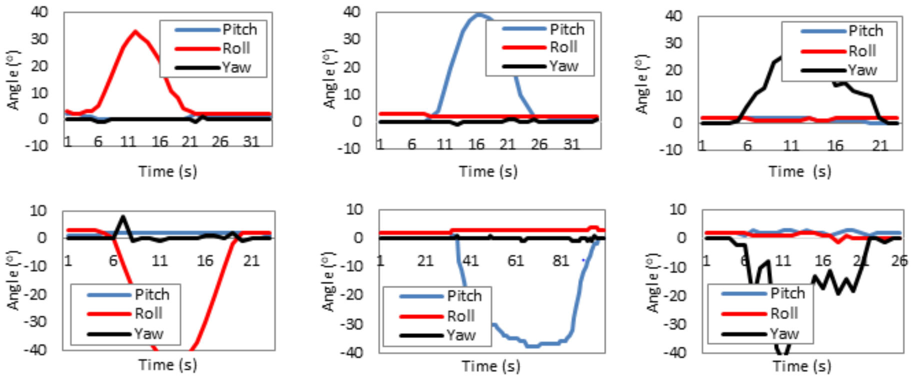
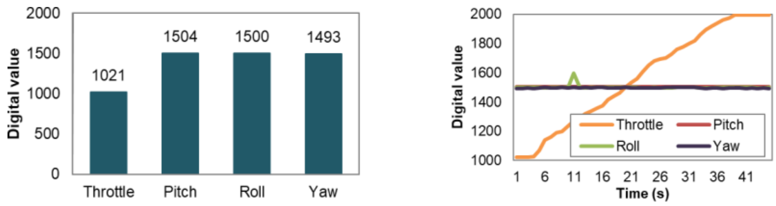
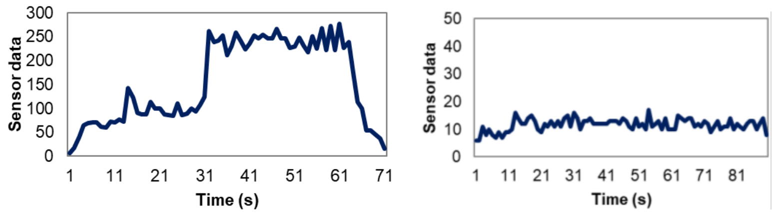


Figure 6. IMU sensor responses



(a) (b)

Figure 7. Digital value from remote control at (a) initial condition and (b) throttle change



(a) (b)

Figure 8. Sensor reading signal (a) before and (b) after balancing

Table 2. PID Constants

Constants	Roll (θ)	Pitch (φ)	Yaw (ψ)
P	1.3	1.3	4.0
I	0.04	0.04	0.02
D	18.0	18.0	0

The experimental test is conducted to see the PID control performance when quadrotor flight. PID constants in Table 2 are used to control the quadrotor in accordance with PID control signal equation. The test result shows that PID controller able to stabilize the quadrotor attitude. This is shown by the third attitude responses which are described in Figure 9. Based on test result above, the attitude responses are well-controlled when PID controller is employed. The controller is able to produce the stable responses with estimated settling time for roll, pitch, and yaw respectively by 2.78 s, 5.37 s, and 0.94 s. The maximum overshoots obtained are -25.70°, 24.01°, and -17.09° for roll, pitch, and yaw respectively. However, the controller still produces the overshoot at transient condition. The best performance of controller can be achieved by increasing the robustness of controller design as well as PID constant optimization. Figure 10 shows the control signal produced by PID controller. This signal is obtained based on PID equation and plotted according to the attitude responses in form of digital value. For completeness, the quadrotor that used in this study is shown in Figure 11.

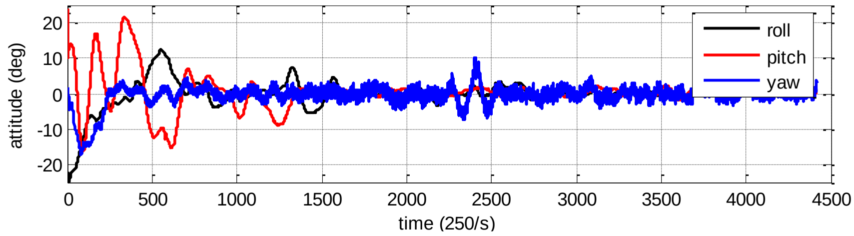


Figure 9. Quadrotor attitude responses with PID controller

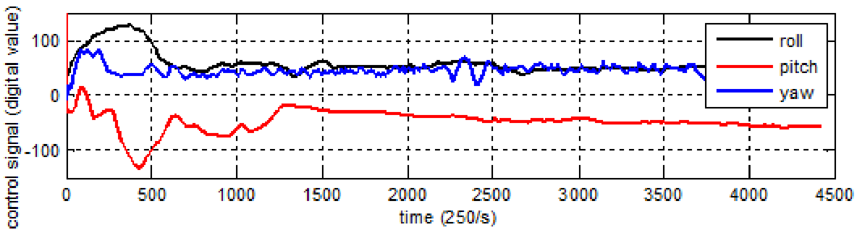


Figure 10. Control signal

(a) (b)

Figure 11. Quadrotor at (a) take off and (b) flying conditions

4. Conclusion

A Low-cost design of quadrotor with PID control system has been presented in this paper. Based on research result, it is concluded that the quadrotor hardware can be built with relatively low-cost components that available in many electronic markets. Designed quadrotor is cheaper if compared with several low-cost quadrotors that mentioned in this paper and other commercial quadrotor. The quadrotor can also be controlled using simple control system methodology like PID controller. Quadrotor attitude looks stable with PID controller even though there is still overshoot. Nevertheless, this result is acceptable and as expected when we design the controller with simple and rapid methods. Further researches are needed to enhance this low-cost quadrotor as well as designing robust controller, hardware improvement, and developing its utilization.

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