Inverted Pendulum Stabilization with Flying Quadrotor

Werdi Wedana Gunawan, Aresti Likafia, Endra Joelianto and Augie Widyotriatmo

***Abstract*—Quadrotor flying hoverboard is a future technology with applications in various fields such as sports, recreation, military, disaster mitigation and urban transportation. In this paper, it is developed a quadrotor flying hoverboard system that stabilizes an inverted pendulum controlled by a PID controller. The implementation of the PID controller begins with the design of the hardware and prototype, followed by the system modeling, and continued by the PID controller design and the safety system. The control system consists of two PID controllers switched at a specified angle of the inverted pendulum position. The PID controllers with optimized parameters and fine tuning give the best response of the output roll angle inverted pendulum although there occurs time delay about 0.2 s.**

***Index Terms*—Quadrotor, Flying hoverboard, Inverted pendulum, Dynamics modelling, PID controller, Tuning, Remote operation and control**

I. Introduction

FLYING hover board is one of the PAV (Personal Aerial Vehicle) that has been widely developed nowadays. Based on CNN news, flying hover board is a future technology applicable in any fields such as sports, recreation, military, disaster mitigation and urban transportation [1]. Flying hoverboard with its rider is an unstable physical system so that small disturbances can make the rider roll over and fall. The design of an autonomous control system is one of the main challenges faced in its development [2].

In this paper, the flying hoverboard system is considered as a quadrotor [5] and the rider as an inverted pendulum [6]. The problem is then how to stabilize the inverted pendulum at the upright position by moving the quadrotor. As a preliminary effort to achieve the stabilization objective, the paper considers the control design based on the model of the flying quadrotor. The well known PID controller is then implemented on the inverted pendulum-flying quadrotor (IPFQ) considered at constant altitude to keep the angle of the pendulum roll upside down and the y-axis position of the quadrotor on the zero steady state error.

Due to nonlinear nature of the IPFQ, switched PID controllers are selected to perform control actions at different angle values. The switched PID controller can be implemented thanks to the advancement of sensor technology, communication and information technology, and microcontroller technology in the subject of quadrotor. Flight controller used in this paper is APM 2.6 (Ardupilot Mega) and ground control software is MP (Mission planner) both of them communicate through a telemetry module. Important features of APM 2.6 and MP are quadrotor configuration, system identification, and data processing.

The main principle in keeping the inverted pendulum to have a zero of roll steady state error is by providing precise acceleration on the quadrotor. The inverted pendulum stabilization uses a feedback signal generated by the PID controller from the reading of angle sensor (analog joystick), quadrotor position and angle sensor (MPU 6050). Furthermore, the PID controllers generate pulse signal based on controller algorithm, then it is forwarded to the APM 2.6 flight controller. After that, APM 2.6 sends the PPM signal to the propulsion system so that the quadrotor can move according to the y-axis acceleration or roll angle to stabilize the inverted pendulum.

II. MATERIALS

A. Devices

The experiment uses the following devices which are quadrotor, inverted pendulum, controller system (Arduino Uno), Analog joystick FrSky Gimbal PR10, MPU 6050, and data logger shield. The body of quadrotor on the experiment is self asemblied consists of a flight controller APM 2.6, GPS Neo 7M, propulsion system (30A brushless ESC, black propeler 1045, and brushless motor Turnigy Aerodrive), frame DJI F450, LiPo battery, remote control Futaba T7C, receiver Futaba R617S, modul telemetry 3DR 433 MHz, Universal Tall Landing Gear Skid, and propeller guard DJI.

The quadrotor includes 6 degrees of freedom: the transalational position (x, y, z) is measured in inertial coordinate system and the vehicle altitude is defined by three

Manuscript received August 16, 2017. This work was supported by the Ministry of Research, Technology and Higher Education of the Republic of Indonesia under the Decentralized Research Program on Higher Education Excellent Research, Bandung Institute of Technology, Indonesia 2016.

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Euler angles, such that yaw (rotation from z_B axis), pitch (rotation from y_B axis), and roll (rotation from x_B axis) as shown in Fig. 1 [4].

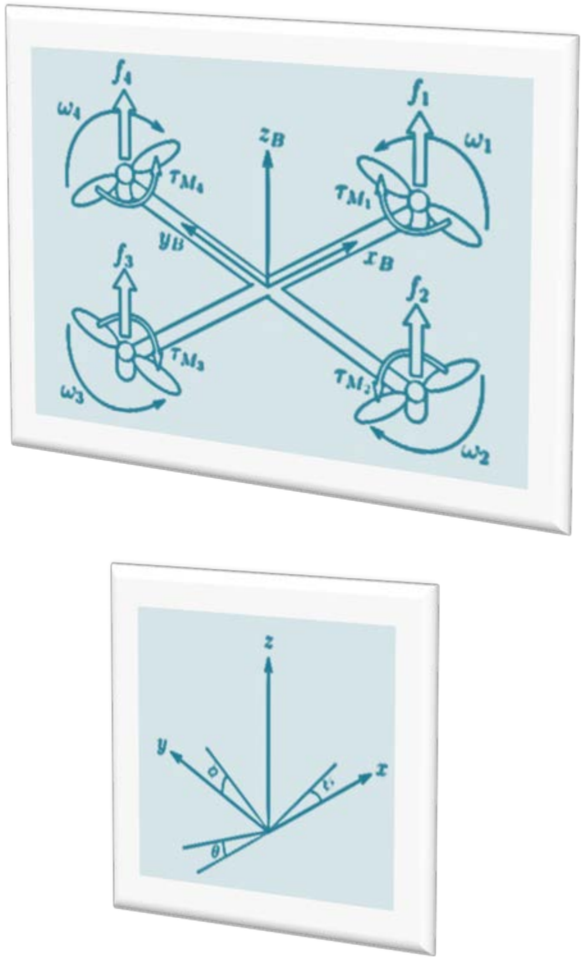

Fig. 1. Coordinates system of quadrotor [11]

The control system is a microcontroller board based on the Atmega 328. It contains 14 digital input/output pins (of which 6 suitable for PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB link, a power jack, an ICSP header, and a reset button. It comprises the whole thing demanded to back up the microcontroller; simply connection to a computer with a USB cable or power it by means of a AC-to-DC adapter or battery [13].

MPU 6050 is a 6 DOF sensor consisting of three accelerometer values to measure the translational acceleration of the quadrotor and three gyroscope values to measure the rotation speed of the quadrotor [7]. MPU 6050 is a sensor based on Micro Electro Mechanical Systems (MEMS) technology. Accelerometers and gyroscopes are embedded in a single chip. The IMU quadrotor is generally used to measure yaw, roll and pitch angles of the quadrotor. MPU 6050 includes three 16-bit analog-to-digital converters (ADCs) for digitizing the gyroscope outputs also three 16-bit ADCs for digitizing the accelerometer outputs.

Analog joysticks are two potentiometers linked altogether, one for two-dimensional movement, one for roll and other movement for pitch movement [8]. The spesification of Analog joystick FrSky Gimbal PR10 has spesification of rated voltage DC $5\,V$, total resistance $2.4\,k\Omega$, linearity 6%, and electrical rotation angle $80°$ [12].

B. Software

The experiment used several software which are Arduino IDE 1.6, Sublime Text 2, Mission Planner, Matlab and MS Excel 2010. Mission Planner is a full featured land station application for the ArduPilot open source autopilot development. It is only well-suited with Windows. Mission Planner is used as a construction function and a dynamic control addition for quadrotor [9]. Sublime text 2 is used the external editor of Arduino Uno's code and Arduino IDE 1.6 is used to compile and uploding the code. Matlab is used to identify the dynamics of inverted pendulum and dynamics of velocity y axis versus the pulse singnal of controller. Meanwhile, MS Excel is used to filter the data.

C. Data Communication

MPU 6050 uses Inter-Integrated Circuit (I2C) protocol in communicating to the controller at $400kHz$. It always acts as slave. The LSB of the I2C slave adress is set by pin 9 (AD0). Its logic level for communication with the master is established by voltage on VLOGIC. The I2C data bytes are outlined to be 8-bits long. There is no limitation to the number of bytes transmitted per data transfer. Each byte transfered must be trailed by an acknowledge (ACK) signal. The clock for the acknowlede signal is created by the master, while the receiver creates the actual acknowledge signal by pulling down SDA and holding it low in the HIGH portion of the acknowledge clock pulse [14]. The figure 2 depicts circuit attached to I2C bus.

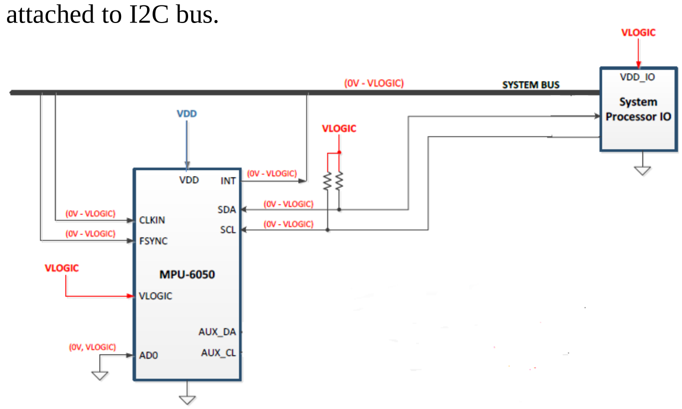

Fig. 2. Circuit I2C bus MPU 6050

Arduino Uno uses pulse position modulation (PPM) protocol signal in communicating with radio receiver Futaba R617S and APM 2.6. The receiver itself consist of 7 channels that describe the desired pitch, roll, yaw, elevator, and three others switch AUX1, AUX2, and AUX3 [15] . The benefit of using PPM protocol is less wire required. Its PPM signal is created every 20 ms. The value of each channel is represented as 1 ms to 2 ms. It goes high ($5\,V$) for the $1-2\,ms$, then it falls to low ($5\,V$) as shown in Fig. 3 [15]. The duration of 7 respective pulses indicate the position of the channel's stick on remote control as depict in Fig. 4 [10]. The position of stick roll, pitch, yaw and roll of remote control represents the desired roll / velocity y axis, pitch / velocity x axis, yaw and the velocity/ position z axis of quadrotor.

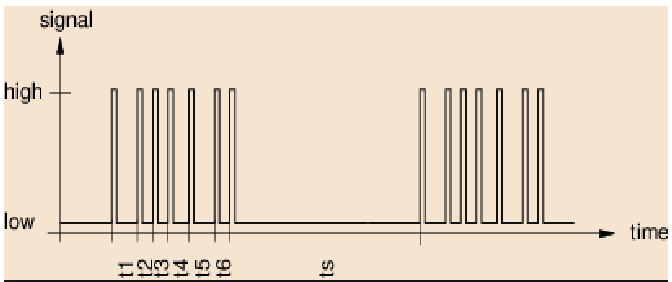

Fig. 3. PPM signal [16]

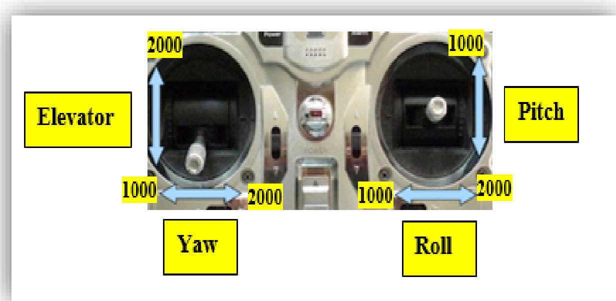

Fig. 4 Position of channel's stick

The reciver and Futaba R617S and remote control Futaba T7C communicate via radio frequency $2.4\,GHz$. Meanwhile the telemetry modul is communicating via radio frequency $433\,MHz$. Moreover, APM 2.6 and ESC use the PWM protocol to communicate. It has standard PWM $1000\,\mu s - 2000\,\mu s$ pulse length which is related to 0% to 100% throttle.

III. METHODS

A. System Modeling

The inverted pendulum dynamics with one degree of freedom at constant altitude are given by the roll angle of inverted pendulum's equation relative to the body frame and the quadrotor position y axis relatif inertial frame as shown in Fig. 5. The dynamics are given as following equations [4]

$$\ddot{r} = r\frac{g}{L} - \alpha g \tag{1}$$

$$\ddot{y} = \alpha g \tag{2}$$

where r and y respectively represent the center mass position of inverted pendulum relatif to the body frame and the lower tip of inverted pendulum relatif to inertial frame, L is the distance of the tip of inverted pendulum to its center mass, α is the roll angle of quadrotor, and g is the acceleration of gravity.

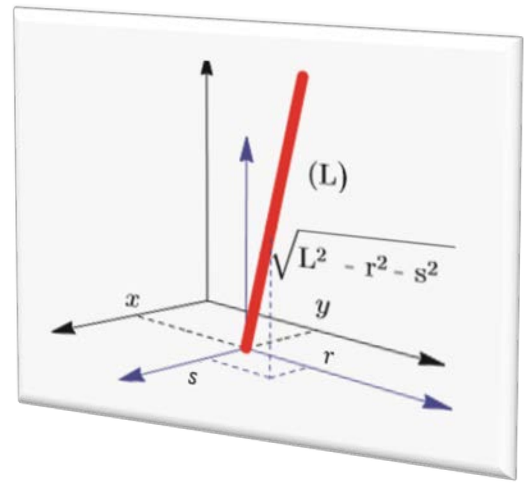

Fig. 5. The position of inverted pendulum according to inertial and body frame [8]

B. Design of Hardware and Prototype

Design of protoype is aim to demonstrate the PID controller to stabilize the upright position of the pendulum by flying the quadrotor. To meet the control objective, first it is needed to build the general of system diagram as shown in Fig. 6. The controller reads the input sensor from MPU 6050 and Joystick FrSky Gimbal PR10, decodes the PPM (pulse position modulation) signal from the remote control receiver Futaba R617S, then processes the algorithm of controller, and finally creates the output PPM signal to the flight controller.

The input PPM signal to flight controller APM 2.6 Mega and the reading position from GPS and compass will decide the pulse signals to the electronic speed controller (Simonk 30 A) for the four rotors. The ESC then will draw current for baterai Li-Po 3S 2.2 Ah to rotate the brusheless motor DJI 2212 920 kV and propeller Gemfan 10×45, and to move the quadrotor on y axis in order to stabilize the inverted pendulum. The power module current sensor 3DR takes part in regulating the power distribution to the ESC and flight controller. Moreover, the flight data will be saved on the onboard-logging memory on the APM 2.6. Further, the data acquisation is used to identify the dynamics of quadrotor and inverted pendulum both using MS Excel to filter the data and Matlab to create the model.

The ground control station used to supervise the flight data in real time by the telemetry Radio USB modul and PC which is installed with software Mission Planner. The GCS will monitor the necessary data such as PPM signal from the controller, quadrotor velocity and altitude, and GPS signal and make decision about the flight which delivers information to the pilot. The pilot uses channel 5 to switch the flight mode from manual flight to autonomous flight when the desired altitude is achieved.

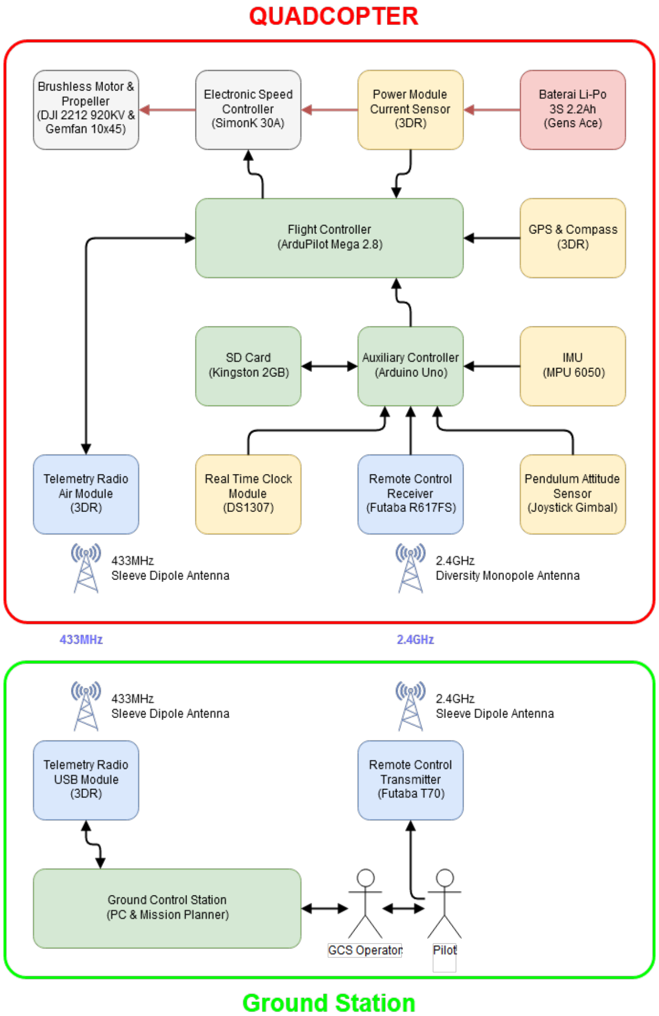

Fig. 6. General diagram of system

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The IPFQ is built based on the system diagram, it consists of two main components: quadrotor as an actuator, and an inverted pendulum replace the human as shown in Fig. 7.

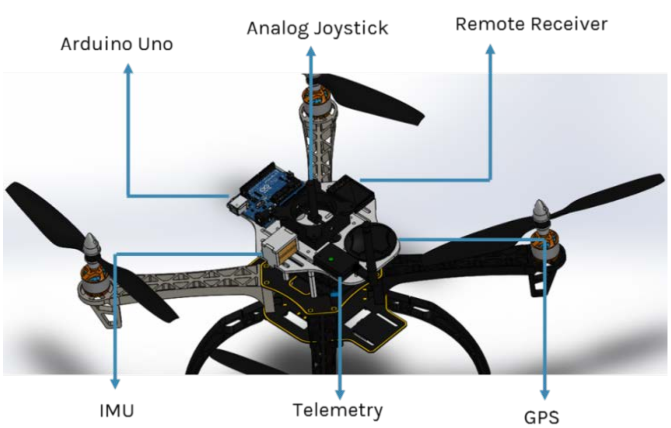

Fig. 7. Top view of the prototype design

The wiring diagram of flight controller APM 2.6 and the controller are shown in Fig. 8 and Fig. 9. The APM 2.6 is connected to ESC, telemetry, Arduino Uno, power module, GPS, and Airspeed sensor. Arduino Uno will send ppm pulse input from output pin 10 to the input pin 1 APM 2.6. Telemetry is connected to pin telemetry on APM 2.6. The APM 2.6 output pin 1,2,3 and 4 send PPM sinyal to the four ESCs. The APM 2.6 GPS pin is connected to the GPS. The ESC will draw the current from LiPO battery based on the input sinyal from APM 2.6. Power distribution board will distribute the power on each ESC and APM 2.6.

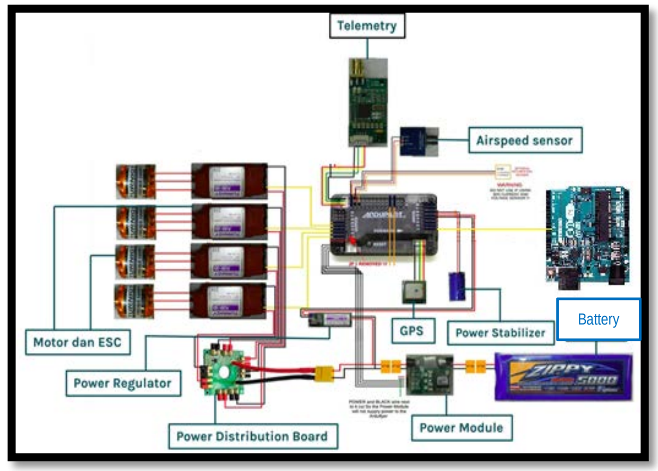

Fig. 8. Wiring diagram of flight controller APM

On the other hand, Arduino Uno is connected to IMU (MPU 6050), Joystick (FrSky Gimbal PR10), data logger shield, RC receiver (Futaba R617S), and APM 2.6. Data logger shield is attached above the Arduino Uno. The pin SCL and pin SDA of MPU 6050 are respectively wired with pin A5 and A4 of analog pin Arduino Uno. Pin VRX and VRY of FrSky Gimbal PR10 are wired to A3 and A4 of Analog Joystick. Channel 7 of Futaba R617S is respectively wired to digital pin 2, VCC and GND.

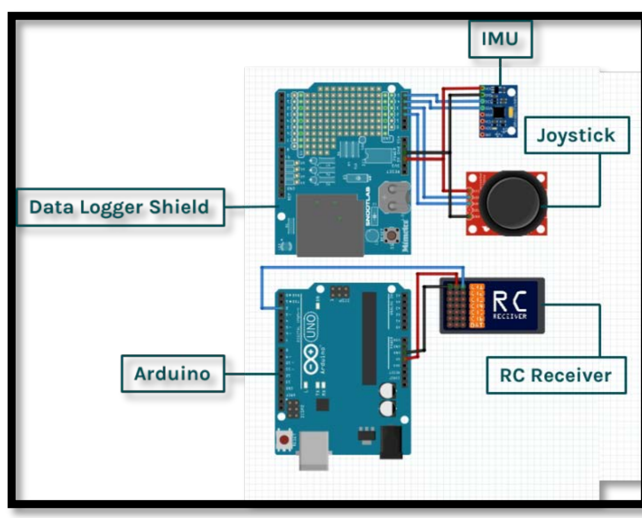

Fig. 9. Wiring diagram controller Arduino Uno

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C. Design of PID Controller

The purpose of designing a PID controller is to define the parameters K_p, K_i, and K_d. The steps in performing PID design are the determination of system physical model, system identification, and PID parameter determination using PID tuner. The control structure of the system can be described as shown in Fig. 10. The controller is made up of two PID controllers of the PID type for small angle and the P type for bigger angle. MPU-6050 reads the roll angle of the quadrotor. The analog joystick reads the roll angle of inverted pendulum relative to the quadrotor θ that is read as a pendulum error. The PID controllers creates the correction by making the output pulse signal u_y. The signal is then transmitted to the flight controller to give the the quadrotor's acceleration in such way to stabilize the inverted pendulum.

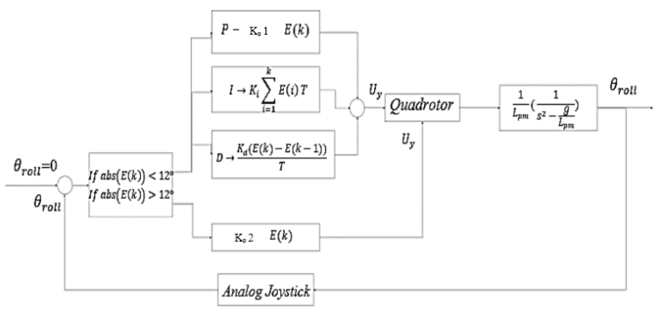


Fig. 10. PID's Control structure

The physical model of the system is represented by the equation (1) and (2) still need the identification because the quadcopter does not create the acceleration directly but first it is received the input pulse signal from controller and then computed by the flight controller APM 2.6 to generate acceleration. It means the the equation (2) should be modified to define the relation of the pulse signal input u_y and quadcopter y axis acceleration $\ddot{y}$. Moreover, the inverted pendulum cannot be represented as single rod because there is a joint with the analog joystick. It means the analog joystick and inverted pendulum rotated coaxially. The equation (2) should be modified to define the relation of acceleration of roll angle inverted pendulum with its roll angle when the acceleration of quadrotor is zero. Finally we have to combine both of dynamic quadrotor and inverted pendulum to form the relation of pulse input signal and roll angle of inverted pendulum as shown in equation (3)

$$\frac{\theta_{roll}}{U_y} = \frac{3.545s^2-0.02376s}{s^4+1.879s^3-7.155s^2-19.84s-35.96} \quad (3)$$

The simulation on Matlab gave the best respon of the paramater of PID controller is $K_p = 15$, $K_i = 5$ and $K_d = 30$ as shown in Fig. 11. Based on the a simulation results, the PID controller is able to stabilize the inverted pendulum. When the disturbance of impulse signal is applied, the system has a settling time of 0.2 s and a maximum amplitude of 17 °.

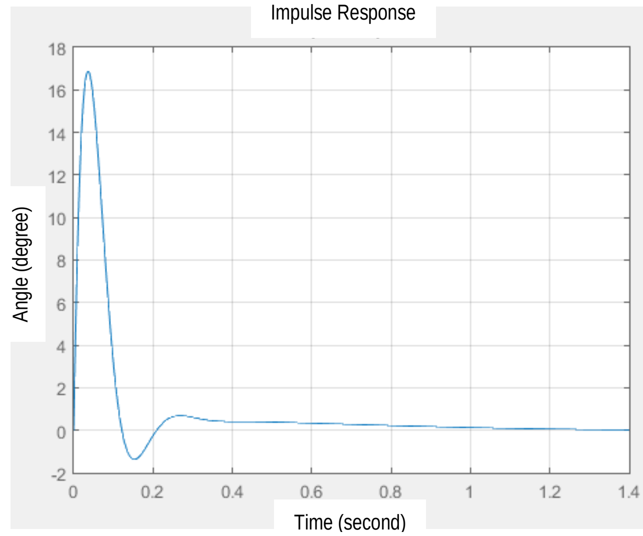


Fig. 11. PID controller simulation (Impulse Response)

D. Design of Safety System

Safety is crucial part of flying a quadrotor. Safety instructions are made not only to protect quadrotor but also for pilot and human safety around it. Hereby in this research there are four types of safety component which are angle limiter, flight test scenario, PID controller safety features and flight test checklists.

IV. RESULTS AND DISCUSSION

The algorithms presented herein were implementing in the espIaned area which sometimes quite windy. The quadrotor took off with stabilize flight mode, then after got the desired altitude the quadrotor enter loiter mode, finally the quadrotor will enter the autonomous mode to stabilize the inverted pendulum. Data are processed from onboard logging from flight controller APM 2.6 that is plotted by Mission Planner.

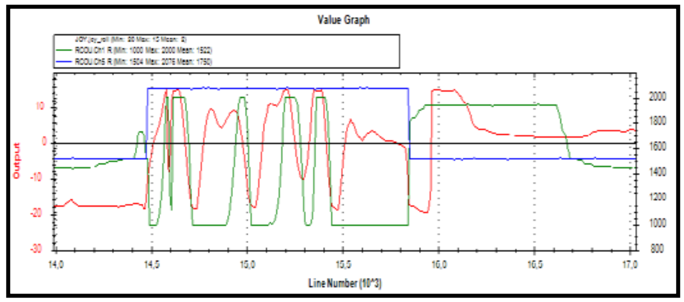
The stabilization principle of inverted pendulum can be elaborated from Fig. 12, Fig. 13, and Fig. 14. First the situation of the roll angle of the inverted pendulum is counter clockwise and the quadrotor moves to the right (Fig. 12.). Then the quadrotor changes the flight direction to left in order to create the centrifugal force to the left in order to reduce the roll angle error of the inverted pendulum (Fig. 13). As the error angle is getting smaller the quadrotor slows down the movement to make the steady state error becomes zero (Fig. 14).

Fig. 12. Quadrotor still moves to the right while inverted pendulum roll to the counterclowkwise

Fig. 13. Quadrotor then moves left to stabilize the inverted pendulum

Fig. 14. Quadrotor slows down to move left as the error of roll angle of inverted pendulum becomes smaller

Fig. 15 shows the result of the implementation of the PID controller. The value of the parameter PID is $K_p\ 1 = 20$, $K_p\ 2 = 50$, $K_i = 5$, and $K_d = 25$. The autonomous flight was indicated by the value of the flight mode graph 2000. The flying inverted pendulum maintained on the autonomous flight in interval line number $4.5 \times 10^3 - 15.85\ \times 10^3$ that was equivalent with $5.4s$. The setling time time of the roll angle output was $0.8\ s$ which had the same order with the simulation result. The maximum overshoot of the roll anggle output was $17°$ matched with the simulation result.



: Roll angle of inverted pendulum

: Pulse sinyal input from Controller

: Flight mode

Fig. 15. Result of the implementation of the PID controllers

The PID controller only gave quite short duration of the autonomous flight. It was because of the parameter of controller did not change with time. As we know there is change of systems because of lifting force of the propeller was reduced by the reduction of power on battery. Moreover, the quadrotor and controller may not be ideal. The controller has time delay about $0.2\ s$, so the input pulse signal from controller was late to compensate the error of the roll angle inverted pendulum. Beside that, the result of the curve fit of the output model and the measured output only had accuracy $67.9\ \%$ which indicated lot of error.

V. Conclusion

In this paper, it was considered the switching PID controllers between the proportional-integral-derivative (PID) type and the proportional (P) type to stabilize the inverted pendulum using the quadrotor. Experiment results showed that the switched PID controllers with parameters $K_p\ 1 = 20$, $K_p\ 2 = 50$, $K_i = 5$, and $K_d = 25$ gave the best response from the output roll angle of the inverted pendulum. The PID controllers were only able to control in quite short duration of the autonomous flight since the parameters of the controllers do not change with time.

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