Jurnal Teknologi

Full Paper

IMPROVEMENT OF QUADROTOR PERFORMANCE WITH FLIGHT CONTROL SYSTEM USING PARTICLE SWARM PROPORTIONAL-INTEGRAL-DERIVATIVE (PS-PID)

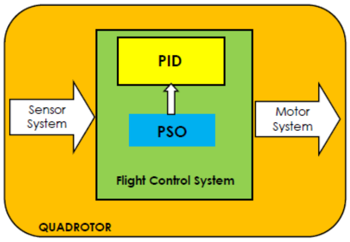
Article history
Received
10 March 2017
Received in revised form
7 June 2017
Accepted
10 August 2017

Andi Adriansyah[a]*, Shamsudin H. M. Amin[b], Anwar Minarso[a], Eko Ihsanto[a]

[a]Department of Electrical Engineering, Faculty of Engineering, Universitas Mercu Buana, Jakarta, Indonesia
[b]Centre of Artificial Intelligence and Robotics (CAIRO), Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author
andi@mercubuana.ac.id

Graphical abstract



Abstract

The rapid development of microprocessor, electrical, sensors and advanced control technology make a quadrotor fast expansion. Unfortunately, a quadrotor is unstable and impossible to fly in fully open loop system. PID controller is one of methodology that has been proposed to control the flight control system. Unfortunately, adjustment of PID parameters for robust control performance is not easy and still problems. The paper proposed a flight controller system based on a PID controller. The PID parameters are tuned automatically using Particle Swarm Optimization (PSO). Objective of this method is to improve the flight control system performance. Several experiments have been performed. According to these experiments the proposed system able to generate optimal and reliable PID parameters for robust flight controller. The system also has 41.57 % improvement in settling time response.

Keywords: Quadrotor, Flight Control System, PID, PSO, Performance Improvement

1.0 INTRODUCTION

A quadrotor aircraft can take off and land in limited spaces, even hover over a target and fly through narrow space and stay in limited-speed motion object easily. With these advantages, the quadrotor has received a strong of attention in the last period [1]. However, a quadrotor is unstable and impossible to fly in fully open loop system [2]. Performance improvement expected from the new generation of quadrotor is possible through derivation and implementation of specific control techniques incorporating limitations related to sensors and actuators [3]. Different methodologies have been proposed to control the flight control system for a quadrotor [4]. The following approaches have been used for improving the flight control system performance are PID control, backstepping control, sliding mode control, linear quadratic regulator (LQR) control, fuzzy logic (FL) control, neural network and hybrid of them [5].

PID has become one of the selected solutions for many practical control designs such as electronics devices, robotics, and chemical process. There are some researches have been performed to design the flight control using PID [6], [7], [8]. PID controller is used here in order to get adequate performances of quadrotor such as fast response, zero steady-state error, and minimum overshoot/undershoot. PID is used here because it can be designed based upon the system parameters can be estimated precisely.

However, there is problem for implementing of PID controller. In order to achieve robust control performance, parameters adjustment or tuning procedure is required. The tuning process, whereby the optimum values for the controller parameters are obtained is a critical challenge. Many studies were conducted to find the best way for tuning PID parameters in order to get satisfactory performances such as using Fuzzy Logic [9], Genetic Algorithm [10] or Ant Bee Colony [11]. However, some of those methods need complex computation take long time process or trial and error procedures.

The objective of this paper is to addresses the problems of the PID parameters tuning in the flight control system using Particle Swarm Optimization (PSO). The rest of this paper is organized as follows: First, a brief description of the quadrotor is provided. Then, hardware design of quadrotor is described and followed by the flight control design. Section 3 gives some experiment results. Finally, the paper is concluded in Section 4.

2.0 METHODOLOGY

2.1 Quadrotor Model

Quadrotor movement mechanism is a resultant of propeller rotation speed (ω_1, ω_2, ω_3 and ω_4). This composition will generate force on each rotor (F_1, F_2, F_3 and F_4) that affecting motion of the quadrotor body, where θ is the pitch angle, ϕ is the roll angle and ψ is the yaw angle in x, y and z axes, respectively. Coordinates and motion principle of quadrotor is depicted in Figure 1.

Total lifting force to be generated by the motor in order quadrotor can hover is listed in Equation (1). Equation (2) and (3) also shows quadrotor condition to lift up or down, respectively [12].

$$F_1 + F_2 + F_3 + F_4 = \omega = m \times g = FT \qquad (1)$$

$$F_1 + F_2 + F_3 + F_4 > \omega \qquad (2)$$

$$F_1 + F_2 + F_3 + F_4 < \omega \qquad (3)$$

Combination of each rotational speed will make the quadrotor able to maneuver, such as hovering, moving forward and backward, rolling right and left also rotating right and left, respectively.

2.2 Attitude Heading Reference System (AHRS)

Attitude Heading Reference System (AHRS) is a real time data orientation. The data orientation consists of a 3 -axis sensor system that provides three-dimensional position information orientation (yaw, pitch and roll). Usually, AHRS consists of a magnetometer, accelerometer and gyroscope on all three axes [13]. These sensors create inertial sensor system that can fully measure the attitude of objects in 3D space.

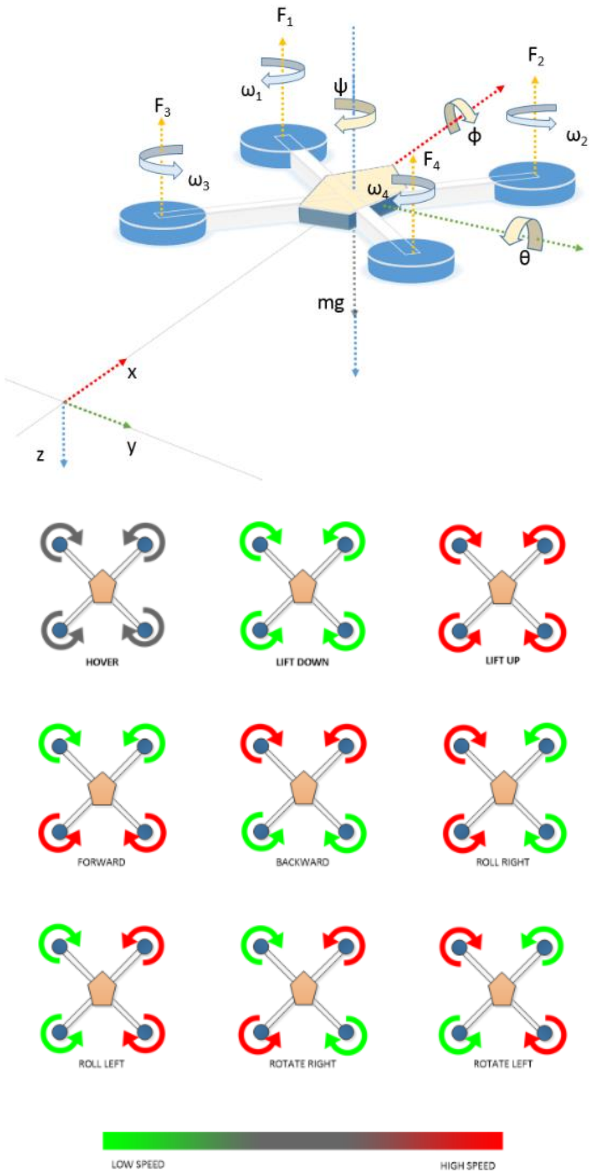


Figure 1 Quadrotor Model and Movement Principles [12]

Quadrotor dynamic movement used state equation and observer equation based on quaternion. Quaternions are mathematically denoted as in Equation (4) and (5), where q_0, q_1, q_2, and q_3 are all real numbers. A quaternion is capable of describing that rotation just right [14]:

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

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

Finally, calculation of the attitude angles based on quaternion are:

$$\begin{bmatrix} \psi \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} \operatorname{atan}(2(q_1q_2 + q_0q_3)/(q_0^2 + q_1^2 - q_2^2 - q_3^2)) \\ \operatorname{asin}(2(q_0q_2 - q_3q_1)) \\ \operatorname{atan}(2(q_0q_1 + q_2q_3)/(q_0^2 - q_1^2 - q_2^2 + q_3^2)) \end{bmatrix} \qquad (6)$$

In order to process the data sensor in quaternion format, Digital Motion Processor (DMP) is used. DMP is a technology planted on inertial sensor chip that is intended to filter the data and process complex calculations quickly [15]. The technology is able to filter the data and process complex calculations quickly. This technology processes sensor data from a chip. Several sensors consist in this chip, such as gyroscope sensor, accelerometer and compass. DMP data packets are measurement data that has been filtered and been formed as quaternion data.

2.3 Quadrotor Design

Typicallyl quadrotor system contains an UAV quadrotor with X-shaped, a ground control and a communication system [16], [17]. Figure 2 shows block diagram of the system that are developed.

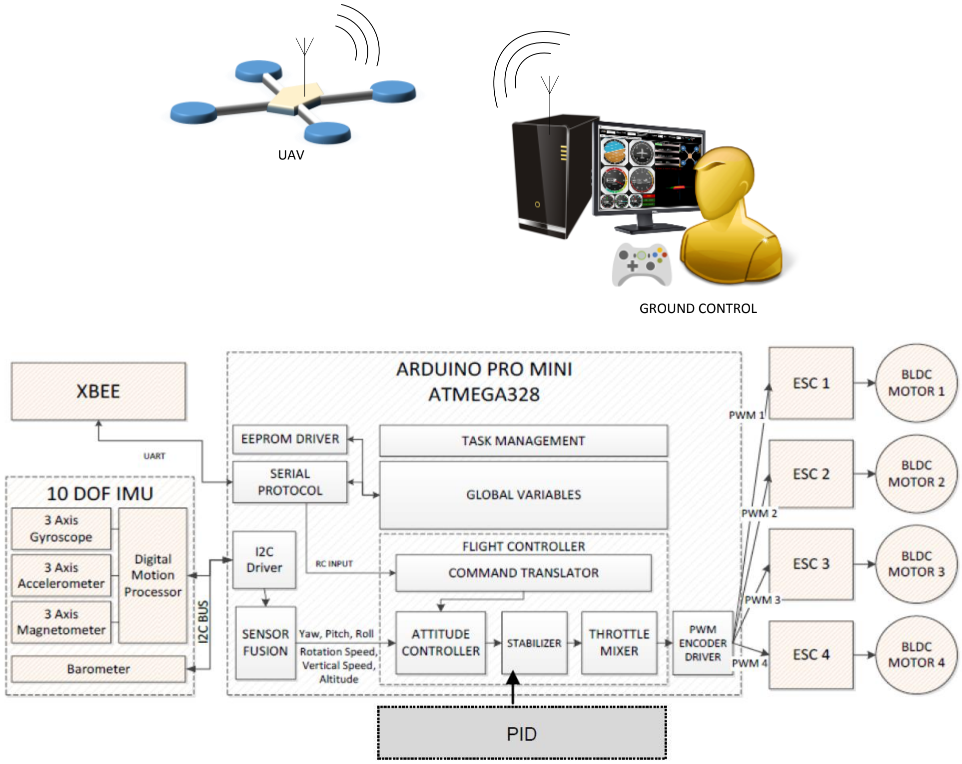


Figure 2 Block Diagram of Quadrotor System

The UAV system design consists of the following component: the brushless dc motor (BLDC), the propeller, the Electronic Speed Controller (ESC) and the battery. The BLDC motors used are Motor SunnySky X224S-16. ESC EMAX12 A is used for speed controller that has PWM input signal and internal Battery Eliminator Circuit (BEC) with 5V/1A rate. Six propeller HQ-PROP is used with 6 inch long and 3 inch pitch. A microcontroller system used is Arduino Pro mini with ATMega328 used to control all quadrotor system. The quadrotor is designed in X-frame type of FPV250 with diameter 25 cm and weight 109 g. The placement of four motors on this frame has the same distance to the center of mass quadrotor. Wireless communications is one of the challenges. Several factors are 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 is used to simplify the circuit and connectivity with a microcontroller or computer.

Drotek 10 DOF IMU is used that contains accelerometer, gyroscope, magnetometer and barometer. The sensor system contains two chips, MPU9150 that contains accelerometer, gyroscope, magnetometer and MS5611-01BA that contain barometer. A DMP system is mounted in this unit. All of the data from the sensors are processed on IMU. The results of these processing are angular position (ψ, θ, ϕ), rotational speed, acceleration and altitude that said as AHRS data. Then AHRS data will be used in flight controller based on PID schema.

2.4 Flight Control Design

Flight Control function is to control the quadrotor from ground control based on AHRS data, such as maintaining the angular position, changing them or maintaining the altitude of quadrotor. Outputs from flight controller then are distributed to BLDC motor, respectively. Two modes of flight controller are designed as acrobatic mode and angle mode. Flight Control block diagram is depicted in Figure 3.

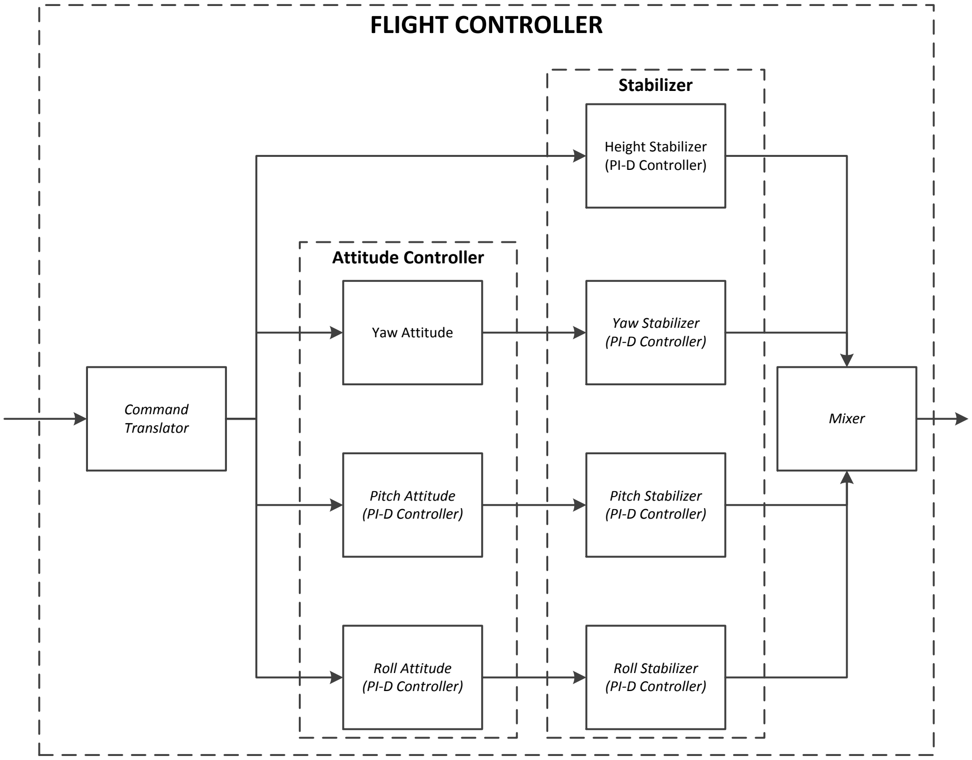


Figure 3 Flight Control System Block Diagram

In this research, Flight Control is designed using PS-PID Controller. Basically, PS-PID is a PID controller augmented by a tuning or learning process based on PSO. In PS-PID, PSO is applied in order to search for PID parameters for a particular problem and to ensure those parameter values are optimal with respect to the design criteria. PSO is one of evolutionary computation technique developed by Kennedy and Eberhart 1995 [18-19].

The PSO process starts with randomly generated initial populations. Then, all populations of particles are evaluated iteratively use:

$$v_i^{k+1} = v_i^k + c_1 * rand(.) * (pbest - s_i^k) + c_2 * rand(.) * (gbest - s_i^k) \tag{7}$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{8}$$

where v_i^k, v_i^{k+i} , and s_i^k , are velocity vector, modified velocity vector and positioning vector of particle *i* at generation *k*, respectively. Then, *pbest* is the best position found by particle *i* and *gbest* is the best position found by particle group. Finally, c_1 and c_2 are cognitive and social coefficients, respectively. Updating process of velocity and position of each particle is depicted in Figure 4.

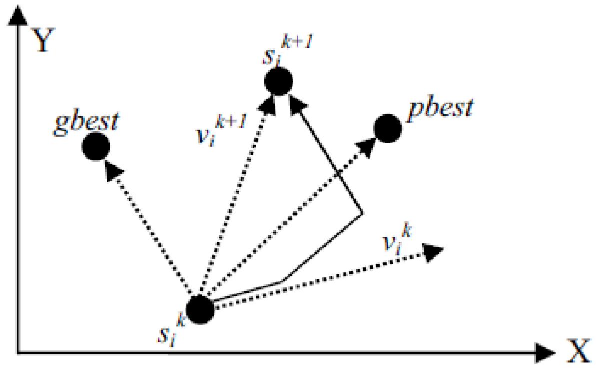


Figure 4 The velocity and position updates in PSO

The PID parameters constitute the optimization space, which is then transformed into suitable position on which the search process operates. Figure 5 shows the concept of a PS-PID system where PSO design and PID processing are the two fundamental constituents.

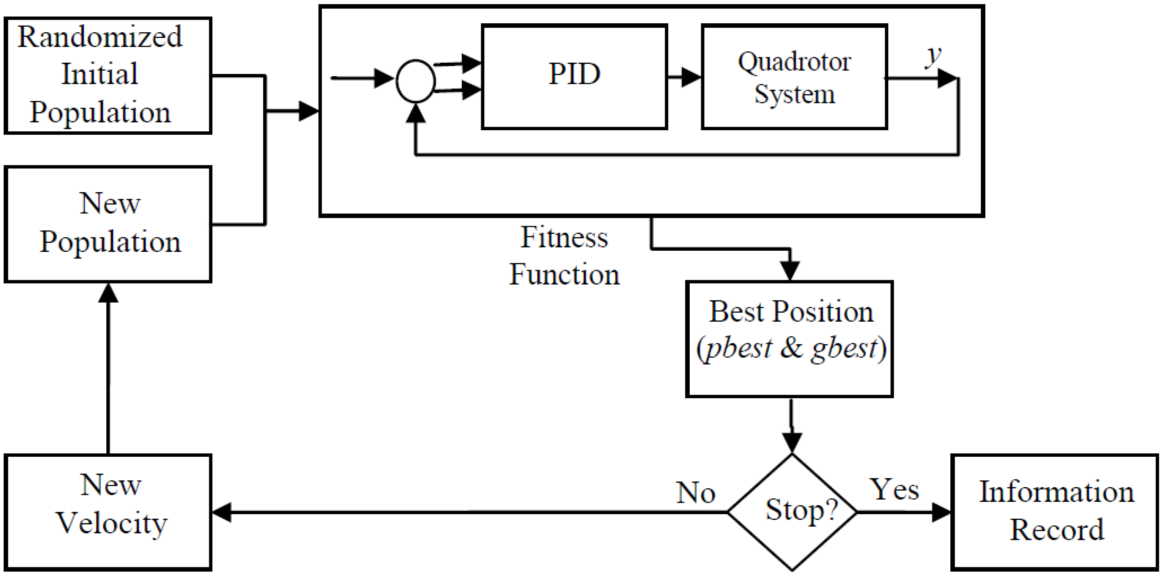


Figure 5 The concept of a PS-PID

As the PSO deals with coded parameters, all parameters that need to be tuned or learned must be encoded into a finite length of string. The encoded strings are concatenated to form a complete particle. In order to learn PID parameter for yaw, roll and pitch control, each parameter is encoded into integer codes that are based on series of Kp, Ki and Kd, respectively. The coded parameters for each control system are arranged to form particles of the population, as shown in Equ (9) and (10):

Particle $$|Kp_1|,|Ki_1|,|Kd_1|,|Kp_2|,|Ki_2|,|Kd_2|,|Kp_3|,|Ki_3|,|Kd_3| \quad (9)$$

Parameter $$|\cdots(PID_1)\cdots|,|\cdots(PID_2)\cdots|,|\cdots(PID_3)\cdots| \quad (10)$$

In this work, a Sigmoid Decreasing Inertia Weight (SDIW) is used to provide faster speed of convergence and better accuracy of optimized value [20][21]. Consequently, PS-PID would generate optimal and reliable PID parameters for robust flight controller.

3.0 RESULTS AND DISCUSSION

The whole of UAV quadrotor based on system design and GUI module are depicted in Figure 6-Figure 8. An X-shape frame Quadrotor with four BLDC motors and ESC, IMU sensors and battery for power supply have been developed. The GUI module designed for showing several input and output measured variables, such as: PID parameters, AHRS values, and some graphical ones. A PC / Notebook connected with XBee module and an Xbox joystick are used as input for flight control.

Figure 6 A UAV Quadrotor System

Figure 7 A UAV Quadrotor System with Notebook and Xbox joystick

COM COM9
Baud Rate 115200
Uplink 50 Hz
Downlink 20 Hz
Received/Loss 62 / 0
THROTTLE - 1000
AILERON - 1500
ELEVATOR - 1500
RUDDER - 1500
W: 1.000, X: 0.000, Y: 0.000, Z: 0.000

Figure 8 A UAV Quadrotor GUI Module

Several experiments have been performed. All of experiments used bench-test equipment as shown in Figure 9. Based on offline experiments of PS-PID, the optimum parameters of PID for flight control system with each angular position respectively is listed in Table 1.

Figure 9 A Bench Test Equipment

Table 1 PID Parameters

Angular Position	Kp	Ki	Kd
Roll	0.7500	0.0205	0.02343
Pitch	0.8500	0.0125	0.02500
Yaw	0.7500	0.0205	0.02343

In order to test the performance of the controller, some responses systems are shown. Other results that use PID for flight control tuned manually [3] are compared. Figure 10 and Figure 11 show response system for roll angular position after given some disturbance.

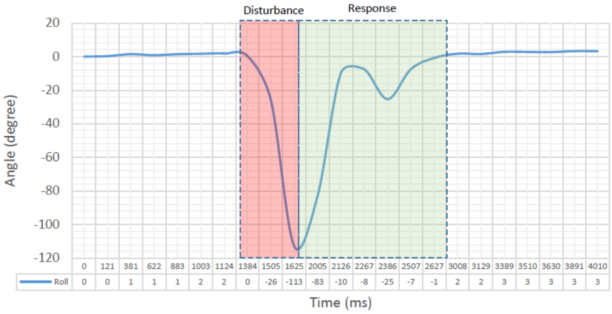


Figure 10 Response Systems for Roll Angular Position with PS-PID

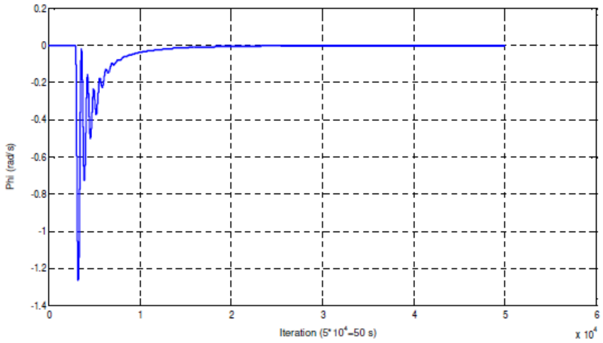


Figure 11 Response Systems for Roll Angular Position with PID [3]

The response system using PS-PID after given certain disturbance has very short oscillation, fast response time in around 1 s and has minimum steady state error, as depicted in Figure 10. However, the response system using PID that tuned manually has very long oscillation with 7s response time and has zero steady state error. Fortunately, both systems have no overshoot.

Response systems for yaw angular position after given some disturbance are shown in Figure 12 and Figure 13. Figure 12 shows that the response system using PS-PID has very short oscillation, fast response time in 1.1 s, has minimum steady state error and has no overshoot. In another side Figure 13 shows that using PID that tuned manually, there is some oscillation, has response time more than 10s, has zero steady state error and has overshoot.

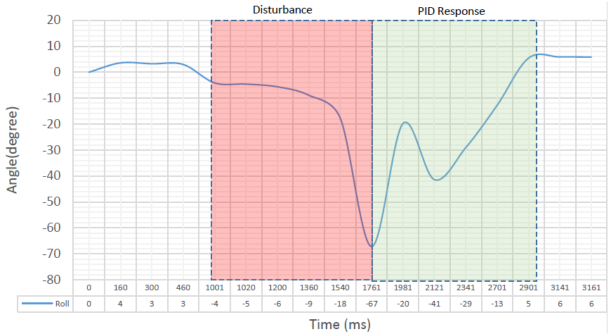


Figure 12 Response Systems for Yaw Angular Position with PS-PID

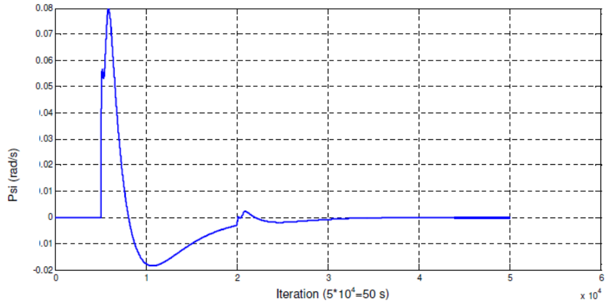


Figure 13 Response Systems for Yaw Angular Position with PID [3]

The last experiments are to see response systems for pitch angular position as shown in Figure 14 and Figure 15.

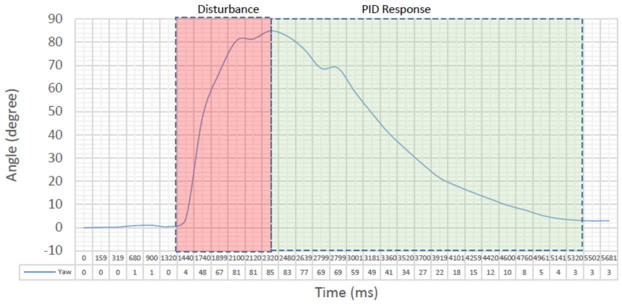


Figure 14 Response Systems for Pitch Angular Position with PS-PID

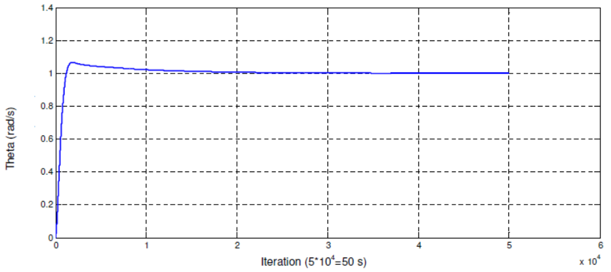


Figure 15 Response Systems for Pitch Angular Position with PID [3]

As experiments before, the response system using PS-PID has very short oscillation, fast response time in less than 3 s, has minimum steady state error and has no overshoot, as depicted in Figure 11. In another side Figure 12 shows that using PID that tuned manually, there is also short oscillation, has response time around than 2s, has zero steady state error and has no overshoot.

Overall, control performance of the designed system offered compared to system that the PID tuned manually has same advantage that both have very small steady state error. However, the PS-PID system has more advantageous, namely the absence of overshoot, short oscillation time and lower time for settle condition. Comparisons of settling time value are shown in Table 2. Table 2 shows that the PS-PID system has a 41.57 % improvement.

Table 2 Time Response Comparison

Movement	Settling Time		Improvement (%)
	PS-PID (s)	Manual PID (s)	
Roll	1.0	7.0	85.7
Yaw	1.1	10	89
Pitch	3.0	2.0	-50
Average			41.57

4.0 CONCLUSION

A flight controller system for an UAV quadrotor has been designed that on Particle Swarm-PID (PS-PID). The UAV system design consists of a frame, motors and propellers as actuators, IMU unit as AHRS data source, microcontroller unit as a control module and wireless unit as supporting communication with ground control. Several experiments have been performed. A system based on manual tuned PID is used for comparison. According to these experiments it can be said that the proposed system able to generate optimal and reliable PID parameters for robust flight controller system. The proposed designed has settling time performance as follows: 1.0s for roll, 1.1s for yaw and 3.0s for pitch. While manual PID just has settling time performance as follows: 7.0s for roll, 10s for yaw and 2.0s for pitch Generally, the system designed has 41.57 % improvement in settling time response compare to previous system.

Acknowledgement

The authors are very grateful to the Center of Research of Universitas Mercu Buana for supporting and funding this research.

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