Particle Swarm Optimization (PSO)-Based Self Tuning Proportional, Integral, Derivative (PID) for Bearing Navigation Control System on Quadcopter

by Sumardi Sumardi

Particle Swarm Optimization (PSO)-Based Self Tuning Proportional, Integral, Derivative (PID) for Bearing Navigation Control System on Quadcopter

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***Abstract*— Unmanned Aerial Vehicle (UAV) is an unmanned aircraft that is controlled manually or automatically over long distances. The quadcopter UAV is rapidly developed in recent years due to various purposes. One of the quadcopter navigation system, the UAV moves towards different coordinates by controlling vertical axis rotation angle (yaw) or bearing. In this research, we propose self-tuning proportional integral derivative (PID) control using particle swarm optimization (PSO) method for bearing navigation. Global positioning system (GPS) is used to determine the coordinates of bearing angle to the destination. HMC5883L compass sensor is used to calculate the actual angle of the quadcopter from the earth electromagnetic field. Based on the test results, the quadcopter successfully holds fixed coordinates with settling time at 6.4s and average error after settling time is 5.4°. Based on test result of coordinate changes, the quadcopter is able to reach the aim as fixed coordinates with average error of 7.9°. In the experiment with disturbance, an average offset error of 1.89° and settling time of 4.1 seconds has been achieved. The best PSO self-tuning limits are obtained at Kp = 0.15 to 0.3, Ki = 0.06 to 0.6, and Kd = 0.005 to 0.1. The PSO values used were C1 = 1.5, C2 = 2 and the weight of inertia from 0.7 to 1.2.**

Keywords*— *Quadcopter, Bearing Navigation, Self Tuning PID, Particle Swarm Optimization

I. Introduction

Unmanned Aerial Vehicle (UAV) is a type of unmanned aircraft controlled manually or automatically over long distance. The quadcopter UAV is rapidly developed in recent years due to various purposes such as environmental monitoring, security, mineral exploration and military. Quadcopter is propelled and lifted by four rotors with crossed frames [1]. One of the development of quadcopter navigation system is by facing the intended location, so that the quadcopter flies then move forward and arrive at the intended location. The parameter to be controlled for the UAV direction is the vertical axis rotation angle (yaw) or referred as bearing.

Different control schemes have been around for UAV control, e.g. PID, LQR, LQG, Backstepping, Fuzzy Logic or neural networks [2][3][4]. Genetic algorithms is one of the best quadcopter control system for six degree of freedom (forward or backward, up or down, left or right, yaw, pitch, roll) compared to other controls, including Neural Network [5]. The compared parameters are adaptive characteristics, precision, speed of convergence response, simplify of algorithm, noise signal and so forth. The Particle Swarm Optimization (PSO) has controlled optimization method by searching for solutions in a heuristic population that is similar to a genetic algorithm [6]. This research explores the development of a self tuning PID with PSO method to be able to control the quadcopter's bearing navigation.

II. Methods and Materials

A. PID Control with self tuning PSO

The design of self-tuning PID control with PSO is used to control Pulse Width Modulation (PWM) signal of yaw angle with the continuous change of set point due to the change of quadcopter coordinate. The value of PID parameters is automatically tuned by PSO. The block diagram of the self tuning PID with PSO method is shown in Fig. 1.

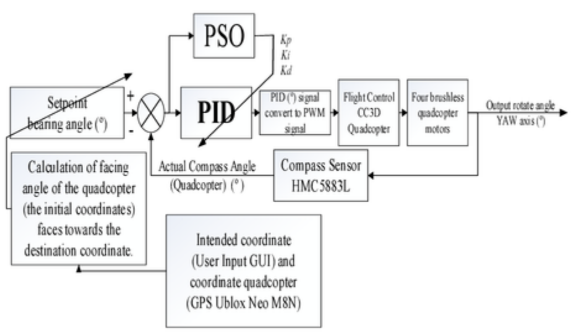

Fig. 1. Controller block diagram.

The equation for self tuning PSO is as follows [7][8][9]:

- Particle velocity equation :

$$V_j(i) = \theta\, V_j(i-1) + c_1 r_1[P_{best,j} - x_j(i-1)] + c_2 r_2[G_{best} - x_j(i-1)] \qquad j = 1,2,\ldots,N \qquad (1)$$

- Inertial weight equation:

$$\theta = \theta\, max - \left(\frac{\theta max - \theta\, _{min}}{error_{max}}\right) error\_actual \qquad (2)$$

- Particle position equation :

$X_j = X_j(i-1) + V_j(i)$
$j = 1,2,\ldots,N \qquad (3)$

- Kp, Ki dan Kd equations from PSO:

$Kp_j(i) = X_j = X_j(i-1) + V_j(i)$
$Ki_j(i) = X_j = X_j(i-1) + V_j(i)$
$Ki_d(i) = X_j = X_j(i-1) + V_j(i)$
$j = 1,2,\ldots,N \qquad (4)$

In order to adjust the PID control, the weight value of inertia uses Eq. (2) so the value of θ will be smaller when reaching set point because the error will decrease when approaching set point. Value of $P_{best,j}$ *is* obtained by doing the PID test directly so there is a different value between $X_j(i)$ and $X_j(i-1)$, then both smallest error values are found. To find the value of $G_{best,}$ the value of all particle $X_j(i)$ in one iteration is tested directly on the PID control system and every time the trial is done, the error value will be compared with $X_j(i)$ and the smallest error will be the value of $G_{best..}$

B. Direction and Coordinate Module

The GPS U-blox Neo M8N is used for coordinate determination. The serial communication system with baudrate 9600 NMEA GGA data format is used. Data of degree minutes (DM) format is then converted to degree decimal (DD) to get the value of longitude and latitude by DD format [10]. GPS format NMEA GGA to DD:

*$GPGGA,******,ddmm.mmmmm,Direction,dddmm.mmmmm, Direction,*,**,*.*,**.*,*,**.*,*,,****

*$GPGGA,******,0703.76714,S,11026.84100,E,***,*.*,**.*, *,**.*,*,,****

Therefore, the data becomes: Latitude format DM: 0703.76714 sign "S", Latitude format DD: -7,062785, Longitude format DM: 11026.84100, Latitude format DD: 110,447350.

HMC5883L compass sensor is used for angle determination. Ii uses I2C data communication with 2 data ports, i.e. SDA and SCL. The compass has 3 axis data with a length of 16 bits. Compass data passes arctan calculation on x and y data. The arctan radian value is converted into angular by factor of $180/\pi$. If $\theta > 0$, the compass data become $360 - \theta$, while $\theta > 0$ then compass data is added by 360 [11].

C. Polynomial Regression Filter

Polynomial regression filter is used to improve the compass value of HMC5883L to reach the correct value. A value improvement is applied using polynomial regression of fourth and second order using Matlab, with the input of "x" from compass sensor and the output "y" is the actual compass value, hence it will get a polynomial equation of fourth order. Here is the approximation with function of order 2 [12]:

- Approximation using polynomial function:

$$y = a_0 + a_1 x + a_1 x^2 + \ldots + a_n x^n \,(x+a)^n \qquad (5)$$

$y =$ value of the data that is supposed to, $x =$ measurement data, $a_n =$ polynomial regression constants, n = number of data.

- Order 2 equation :

$$\begin{aligned} n a_0 + \left(\sum x_i\right) a_1 + \left(\sum x_i^2\right) a_2 &= \sum y_i \\ \left(\sum x_i\right) a_0 + \left(\sum x_i^2\right) a_1 + \left(\sum x_i^3\right) a_2 &= \sum x_i y_i \\ \left(\sum x_i^2\right) a_0 + \left(\sum x_i^3\right) a_1 + \left(\sum x_i^4\right) a_2 &= \sum x_i^2 y_i \end{aligned} \qquad (6)$$

D. Hardware Design

The main hardware was an ARM STM32F4 Discovery microcontroller that manages inputs and outputs of the control system. The inputs of the microcontroller were compass sensor HMC5833L and GPS U-Blox Neo M8N. The compass sensor is used to determine the position of the quadcopter angle from the north axis of the earth and the GPS is used to know the coordinates of the quadcopter. Both inputs were used for the bearing navigation process. Bearing navigation requires starting positions, destination positions and quadcopter facing angles to see that the quadcopter is always facing the goal. The quadcopter output of control process is PWM to control signal on CC3D while Bluetooth is available to view data of sensor, GPS and a control system. The remote control on the CC3D used manually to control the quadcopter in pitch and roll angle. The entire design is shown in Fig. 2.

The mechanical system on the quadcopter used 4 pieces of arm that are used for brushless motors. Mechanical design made with carbon fiber racing type ZMR 250, which is widely circulated in the market with additional frame board for places of electronic components. The frame board for electronic components uses fiber printed circuit board (PCB) to make quadcopter mechanical design simpler. The mechanical design and places of electronic components on quadcopter shown in Fig. 3.

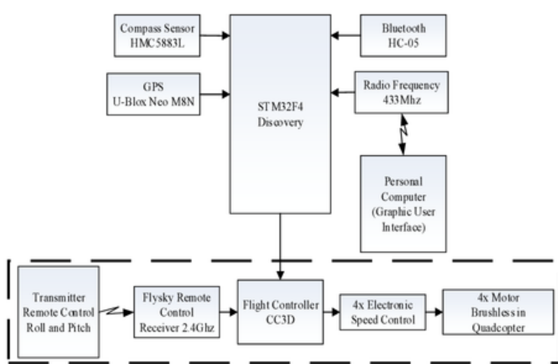

Fig. 2. Design diagram of hardware.

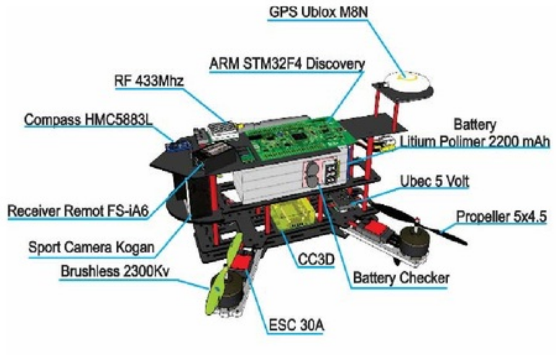

Fig. 3. Mechanical design and position of electrical component.

III. Result and Discussion

A. GPS U-blox Neo M8N Test

The test is to determine the accuracy of GPS because the closer distance between quadcopter with intended coordinates will make quadcopter does not know if the destination point is near or far from quadcopter. Based on the test results with an amount of 2850 GPS data, the maximum error value reached 6.57 meters, minimum error 1.33 meter and average error 3.86 meter. According to this result, if the distance of quadcopter from of the destination point is smaller than 6.57 meters, the control process will not occurs properly.

B. Compass HMC5883L Test

Validity of HMC5883L compass sensor is tested using the digital compass in smartphone as a comparator. Based on the experiment, the data of HMC5883L compass sensor compared with digital compass in smartphone were compensated and fixed by using polynomials regression of fourth and second ordera to correct the value of compass sensor. The equation then becomes:

For x_{20^o-355o}:

$$y = 0.00000005242854118x^4 - 0.00004678548355x^3 + 0.01275813135x^2 + 0.05976890286 + \quad (7)$$

For x_{0^o-19o}:

$$y = 0.0556x^2 - 0.3333x - 346 \quad (8)$$

With the equations above, then the values of the compass can be compensated with values closer to the true value. The following test results are shown in Table 1 after using compensation equation. Table 1 show the maximum error between HMC5883L compass sensor with digital compass in the smartphone. From the test results the biggest error is at 6° with the previous biggest error reached at 22° and average error only 3.4°.

Table 1. Test Result of compass sensor with polynomial regression.

No	Compass sensor (° North)	Compass digital (° North)	*Error* (° North)
1	20	24	2
2	345	348	3
3	359	358	1
4	10	5	5
5	239	245	6
Average			3.4

C. Minimum Error in Yaw Direction Test

This test is used to determine direction of yaw axis rotation angle with the smallest error on the system. The test results shown in Table 2.

Table 2. Minimum error yaw direction result.

No	Actual degree (°)	SP (°)	*Error* CW (°)	*Error* CCW (°)	Rotation Direction
1	77	285	208	152	CCW
2	275	121	206	154	CCW
3	126	185	59	301	CW
4	82	267	185	175	CCW

Note: *CCW: Counter-clockwise, CW : Clockwise*

Based on Table 2, the control system can determine direction of yaw axis rotation, which has the smallest error of the set point. If the error of counter clockwise rotation is greater than clockwise rotation, then the system will choose to rotate counter clockwise because it has a smaller error value. If the error of clockwise smaller than the error of counter clockwise, then the system will choose to rotate clockwise.

D. Limit Value of Kp

Variation test determines the limit value of self-tuning PSO for Kp value between 0.01 to 0.15 and then 0.15 to 0.3 and 0.3 to 0.45. The system response of the three experiments shown in Fig. 4.

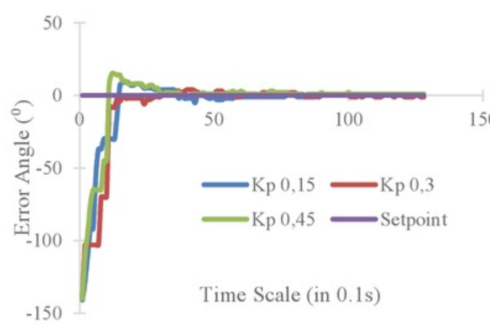

Fig. 4. System response comparison variation of Kp value.

The system response for Kp values of 0.01 to 0.15 has a frequent oscillation characteristic. The system response for Kp values of 0.3 to 0.15 is more stable than the other two values because it has an average offset error at 1.1°, settling time at 2.6s, and less overshoot. The system response for Kp values of 0.3 to 0.45 has very large overshoot if compared to other variations with an error value at 8°.

E. Limit Values of Ki and Kd

The test is used to determine the limit of Ki and Kd values from the best Kp in the previous experiments. The best value for Kp is 0.15 to 0.3, whereas to determine the Ki and Kd there needs a nine experiments with the following variations.

The experiment values for Ki:

- Low values from 0.06 to 0.6 symbolized group (R).
- Medium values from 0.6 to 1.2 symbolized group (S).
- High values from 1.2 to 1.8 symbolized group (T).

The experiment value for Kd:

- Low values from 0.0005 to 0.005 symbolized group (R).
- Medium values from 0.005 to 0.01 symbolized group (S).
- High value from 0.01 to 0.015 symbolized group (T).

The best value comparison from the test results of nine combinations from low values to high values shown in Fig 5.

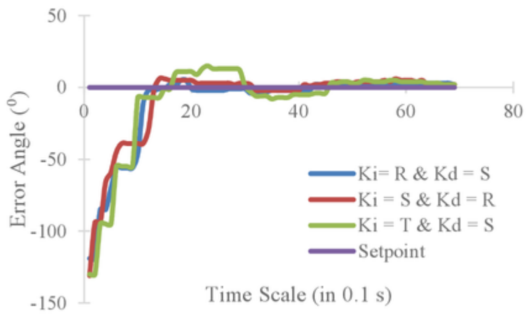

Fig. 5. Comparison of best of three Ki and Kd values.

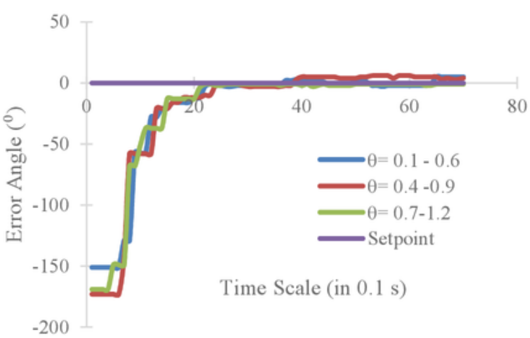

Fig. 6. System response of variations inertial value.

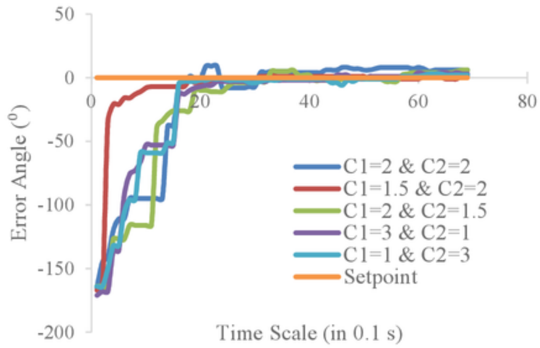

Fig. 7. System response of variations C1 and C2 value.

The system response for low values of Ki and Kd has stable characteristics with the rise time in 1.1 second. the average offset error at 2.31° and the settling time in 1.2 seconds. The system response for medium and low Kd values has a rise time at 1.3 second. the average offset error is 3.28° and the settling time in 1.3 seconds. The system response for high values of Ki and Kd has a rise time in 1 second. the offset error rate is 3.83° and a settling time is 3.9 seconds. Then. the best Ki value was from 0.06 to 0.6 while for Kd was from 0.005 to 0.1.

F. Inertial Weight

The coefficient value of inertia θ is used to update the value from the PSO. The determination of coefficient starts from the low values 0.1 to 0.6 then 0.4 to 0.7 and high values of 0.7 to 1.2. The result of the system response shown in Fig. 6.

In Fig. 6. the test results for the inertial values from 0.1 to 0.6 has oscillation characteristics and reached the steady state at the end of the system response. The test results for inertial values from 0.4 to 0.9 has steady state characteristics because at the beginning of the rise time. the system can achieve set point value. The test results for inertial values from 0.7 to 1.2 has a rise time at 1.5 seconds. the average offset error at 1.34°, and reach the settling time in 2.1 s.

G. Value of C1 and C2

The test of C1 and C2 used to determine the best value of the coefficient from cognitive influence of C1 on the update rate speed of the particle itself. Then, C2 is used to determine the best value of the coefficient from cognitive influence of C2 on the update rate speed because C2 has an effect on changing all particle values. C1 and C2 use variation of values C1 = 2 and C2 = 2, C1 = 1,5 and C2 = 2, C1 = 2 and C2 = 1.5, C1 = 3 and C2 = 1, C1 = 1 and C2 = 3. The result of system response that influenced by C1 and C2 in Fig. 7.

The results for C1 and C2 with value 2 has larger overshoot response and reach error at 9° than other variations. However, the steady state occurs at the end of the system response. The system response for C1 = 1.5 and C2 = 2 has the rise time at 0.6s, the average offset error at 2.16°, and the settling time occurs in 1 second. The system response with the value C1 = 2 and C2 = 1.5 has a slow characteristic with rise time at 1.9 s. The system response at C1 = 3 and C2 = 1 has slow characteristics with rise time at 1.6 s and settling time in 1.9 s. The system response for C1 = 1 and C2 = 3 has slow characteristic with rise time at 1.6 seconds.

H. Parameters Kp, Ki, Kd Changes by Self Tuning PSO

This test is used to know the parameter changes that consisted of Kp. Ki and Kd from self-tuning PSO. The parameters required for the self-tuning process has been determined according to the best trial from the previous test. The best parameter were Kp = 0.15 to 0.3. Ki = 0.06 to 0.6 and Kd = 0.005 to Kd = 0.1. The best coefficient values for C1 was 1.5 and C2 was 2 for weighting of inertia from 0.7 to 1.2. The comparison of parameter changes is shown in Fig 8.

Fig. 8 shows that Kp increases before reaching rise time to speed up the system response. The Kp value decreases after reaching the rise time to reduce the overshoot. The Kp value increases again after steady state to remove steady state errors. Ki values increase before reaching rise time to accelerate the system response. The value of Ki decreases as it reaches the rise time to reduce the occurrence of the system overshoot. The value of Ki increases again after steady state is used to reduce steady state error. The value of Kd increases during the rise time to dampen the P and I control systems so there is no overshoot happens. The value of Kd continues to decrease after the rise time because the steady state moves continuously if Kd is fixed or increased.

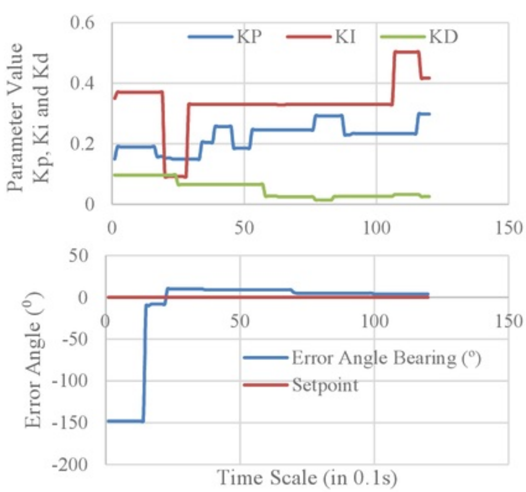

Fig. 8. System response of PID self tuning PSO.

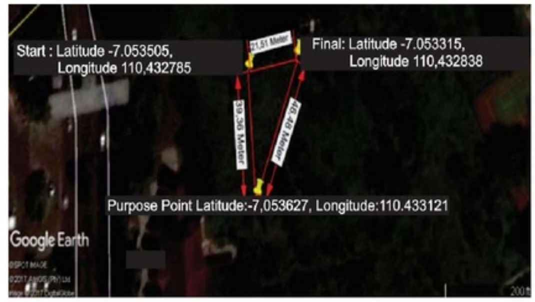

Fig. 9. Point of dynamic test coordinates.

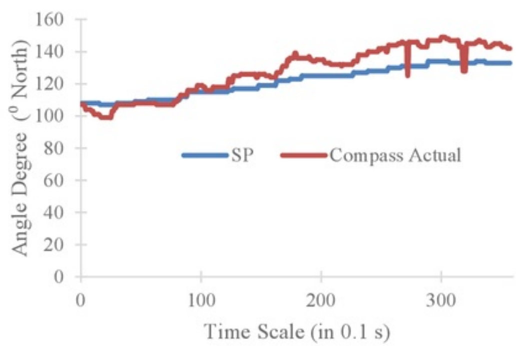

Fig. 10. System response of dynamic test.

I. Dynamic Test

The dynamic test located in Woodball Diponegoro University field. Dynamic test done by moving the quadcopter in horizontal or rolling along 21,51 meters. The test coordinates point for initial quadcopter were latitude -7.053505 and longitude 110.432785 then the final coordinate points of quadcopter were latitude -7.053315 and longitude 110.432838. The destination point of the quadcopter was facing the latitude coordinates -7.053627 and longitude 110.433121. The overall picture of the coordinate point and the distance between the points shown in Fig. 9 and the control system response shown in Fig. 10.

Fig. 10 shows the bearing set point is slowly increasing because in this experiment quadcopter move horizontally to the left so that will add angle value from the bearing set point. The system can follow set point changes from the bearing value with the largest error value is 16°, the average offset error is 7,9° and the minimal error occurs is 1°. By the presence of a set point change, it is shown that steady state occurs in larger angular degrees than the set point or less than the set point. The biggest errors are 16° caused occurs due to the unknown wind speed and direction.

J. Disturbance Test

The disturbance test was conducted in Diponegoro University woodball field. The disturbance was given by rotating the quadcopter directly from the set point in clockwise or counterclockwise. This test was performed to know that the control system can overcome the existence of a fairly high angle error from the existence of disturbance. The quadcopter test at longitude 110.43281 and latitude -7.053328 with bearing or set point 134°. The system response graph is shown in Fig. 11.

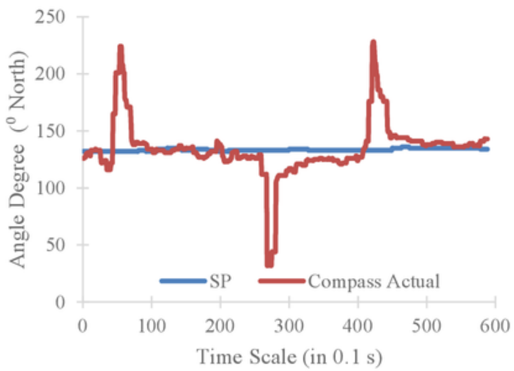

Fig. 11. System response of disturbance test.

The quadcopter test results with disturbance has rise time in 1.9 s (first test), 5.8 s (second test) and 3.5 s (third test). The settling time for the first disturbance test reaches 4.1 second, the second test reaches steady state and the third in 7.3 second. The average offset error in the first test is 1.89°. The second test reaches steady state with the average error after the rise time is 7.89°. The third test average error is 2.98°. The clockwise disturbance occurs if the actual value of the compass exceeds the set point and the reverse rotation of the counter-clockwise quadcopter occurs if the actual value of the compass is less than the set point.

IV. Conclusion

GPS U-blox Neo M8N obtained biggest error in 6.57 meter, the smallest error at 1.33 meter and the error average at 3.86 meter so that the quadcopter bearing navigation is effectively used for distance more than 6.57 meter from destination point. HMC5883L test obtained the largest error of 6° with the average error is 3.4° after filtering. Bearing navigation control system on the quadcopter with PSO-based self-tuning PID control has the best static test results with average error is 5.4° and settling time in 6.4 s. The best dynamic test has an average error at 7.9°. The best disturbance test has an average offset error at 1.89° and reached the rise time in 4.1 s. The best limit values with the 1 test rise time, the lowest overshoot, and the most stable are Kp = 0.15 to 0.3, Ki = 0.06 to 0.6 and Kd = 0.005 to 0.1. The PSO coefficient value obtained through empirical test, from the results, the best coefficient value of C1 is 1.5 and C2 is 2. The best inertia weight coefficient is from 0.7 to 1.2. The overall result shows that PSO-based PID controller is able to determine the coefficient with acceptable values, and

Acknowledgment

The authors would like to thank Dr. Aris Triwiyatno for fruitful discussion in the design of control system. Thanks to staff of Laboratory Control and Instrumentation, Electrical Engineering Dept, Diponegoro University who have provided the facility and support for the research.

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