GENETIC ALGORITHM BASED FOPID CONTROLLER FOR NANO-SATELLITE ATTITUDE CONTROL

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Abstract

Nano-satellite is very popular with researchers in this era because they are more affordable and more comfortable to use than most large satellites. Likewise, the increasing number of researchers in the engineering field came up with the idea of a new mathematical formula in the form of a fraction that was implemented in the control system. The system performance on nano-satellites needs to be improved for the better by using a fractional order PID controller (FOPID), which has never been tested on an unstable system on a nano-satellite object. The development of the PID controller generates two fractional power parameters called the FOPID controller, which makes it even more interesting. Various computational methods have arrived presenting many choices as a solution to finding the optimal control system. The genetic algorithm (GA) produces an optimal computation value on the FOPID controller because it has been proven to have better performance and is improved by the ITAE performance index. Based on the steady-state response analysis in the form of overshoot, rise time, and settling time on the three-axis stable nano-satellite attitude control, namely roll, pitch, and yaw, it can be concluded that the FOPID controller is superior to the classic PID controllers that have been studied previously. The effect of the two parameters of the FOPID controller on the unstable system for controlling the attitude of the nano-satellites shows good performance results based on the ITAE performance index using the Genetic Algorithm (GA) method.

Keywords : genetic algorithm, FOPID controller, nano-satellites

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1. Introduction

The development of satellite technology creates changes in shape from large to small. In many considerations, the control of position movement on large and small satellite sizes will not have many different functions. The use of smaller satellites is cheaper and easier to use, such as nano-satellites currently popular (Sweeting, 2018). Systems with an unstable state and have many problems, especially in attitude control used in nano-satellites, make some good control system modelling solutions.

Several studies have not discussed much position attitude control on nano-satellites using several kinds of controllers and methods. From the controller used, it still has weaknesses, especially in an unstable system for nano-satellite positioning. PID controllers have been used for unstable position movements in satellite nano plants using the MATLAB simulation program. Based on the three-axis control for the satellite control system, it can be explained in simple terms; namely, the x-axis will be the roll angle or rotate up and down, y which will be the pitch angle will move up and down the satellite, and z which will be the angle (Oktodwilavito et al., 2018). Yaw will move up and down the satellite. The simulation results using the auto-tuning and manual tuning methods on roll, pitch and yaw positions on nano-satellites based on previous research can still be optimized (Mashor et al., 2018).

The development of a new idea from the branch of calculus, namely fractional calculus, resulted in a better controller, namely Fractional Order PID (FOPID) which was first produced and developed by Podlubny in 1994 (Cafagna, 2007)(Shah et al., 2016). The FOPID controller has a special form that results from developing a general form of a classic PID controller and has five fixed and additional parameters. From the PID controller, namely the proportional constant (Kp), the integral constant (Ki), the derivative constant (Kd), mu at the power of the fraction of the derivative (μ) and lambda at the fractional integral power (λ) (Shah et al., 2016). All parameter search methods for PID controllers on nano-satellites manually tuning, auto-tuning and smart methods such as metaheuristic have weaknesses for unstable systems and have less than optimal results.

In this case study, parameter optimization was carried out using the FOPID controller on an unstable nano-satellite plant model with roll, pitch and yaw positions. A steady-state is obtained by ITAE criteria using a genetic algorithm that gets the best value of the five FOPID parameters on the nano-satellites' position movement. Comparing the performance of the FOPID controller with the classic or conventional PID based on the system performance in the steady-state from the performance values in the form of the overshoot value, the rise time speed, and the settling time speed. The effect of adding the parameters mu to the fraction of the derivative (μ) and the integral fraction of the lambda (λ) has an optimal impact on the FOPID controller for nano-satellite positional movements.

2. Literature Review

2.1 Fractional Calculus

Fractional calculus is knowledge dating back three centuries before simple or conventional calculus, but it is not very popular in the field of research. Thus many researchers have conducted several studies in various fields of science, engineering, and computers in the last few decades, such as control systems, modeling, signal processing, etc. (Das, 2011).

The first application of fractional calculus was made by Abel in 1823 (K.S. Miller et al., 1993). He found that the solution to the integral equation for the tautochrone problem could be obtained by means of the integral in the form of the half-order derivative. Then research on the use of calculus in the nineteenth century was further deepened for development by Boole in the form of symbolic methods as a condition for solving linear differential equations of constant coefficients or developing solutions for an electromagnetic theory such as example transmission lines using Heaviside's operational calculus (K.B. Oldham et al., 2006). In the twentieth century, fractional calculus has contributed to the theory and application of well-known scientists such as Weyl and Hardy to compose components of integral difference, Erdely focused on integral equations, Riesz based on the function of more than one variable, Scott Blair on rheology, or Oldham and Spanier discovered solutions to electrochemistry and public transportation (Monje et al., 2010). Described here are several definitions of fractional calculus, starting from the definition of n-fold to other variations related to this definition. The fractional calculus definition is also frequently used in the field of control systems (K.B. Oldham et al., 2006).

2.2 PID Controller

The PID controller consists of a combination or the result of the collection of proportional, integral, and derived controllers, and then the three controllers complement each other into one unit.The PID controlling equation can be seen in Equation (1) (C.T. Killian., 2001)(K. J. Astrom., 2006).

$$u(t) = K_p . e(t) + K_p . \frac{1}{T_i} \int_0^t e(t) dt + K_p . T_d . \frac{de(t)}{dt} \quad (1)$$

$K_p . \frac{1}{T_i}$ can be expressed in K_i and $K_p . T_d$ can be expressed in K_d . The form of the Laplace equation can be expressed in Equation (2).

$$U(s) = K_p . E(s) + K_i . \frac{E(s)}{s} + K_d . sE(s) \quad (2)$$

The PID controller's output is the sum of the proportional controller output, the integral controller output, and the derivative controller output. The fundamental nature of the PID controller is strongly influenced by the immense contribution of the three parameters P, I, and D (K. Ogata., 2010).

2.3 Fractional Order PID (FOPID)

The general understanding of the fractional order PID controller is a mathematical development of the classical PID controller. Order-fractional controllers are more responsive to changes in system parameters that are being controlled, and controllers have two additional parameters (Shah et al., 2016). In simple terms, the general transfer function of the PID fractional-order controller (FOPID) is shown in equation (3) (Shah et al., 2016).

$$C(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu}, (\lambda, \mu \geq 0) \quad (3)$$

Can be read broadly, C (s) is the output of the controller, U (s) is the control signal, E (s) is the error signal, KP is the constant proportional gain, KI is constant integral gain, KD is constant derivative gain, strength fractions of λ and μ (Shah et al., 2016). It merely means that the area of the fraction order used is between 0 and 2 and can be many. The classic PID controller is a particular part of the order-fractional controller, where the resulting λ and μ are one, as shown in Figure 1.

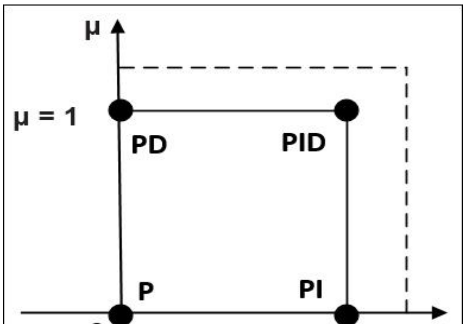

Figure 1. Areas of a PID Fractional Order Controller

2.4 Attitude Determination and Control System (ADCS)

Attitude Determination and Control System (ADCS) is a satellite attitude control system tasked with conditioning the satellite's attitude (Oktodwilavito et al., 2018). Basically, the satellite attitude controller consists of 4, namely: spin-stabilized, graphite gradient, three-axis control, and formation flight. But only spin-stabilized and three-axis control are often used for attitude control on satellites, that is because the properties of the two methods are not much different, namely for spin-stabilized.

Which is rotating using an electric motor that is installed according to the direction of the body, which is the same direction as when we move the head to the right and left is assisted by a small gas jet installed in the body area, while for the three-axis stabilized it uses three rotating axes, namely roll, pitch, and yaw (Oktodwilavito et al., 2018). The following is an overview of the nano-satellite made by nano-satellite researchers, namely InnoSAT shown in Figure 2.

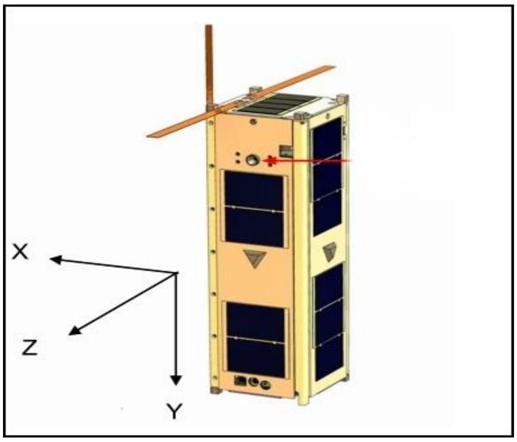

Figure 2. Form of InnoSAT Implementation of Nano Satellite (Fadly et al., 2011)

Has the meaning of body stabilized, which means if the three axes are stable. This research will discuss ADCS that uses body stabilized or what is also known as three-axis stabilized.

2.5 Genetic Algorithm (GA)

Genetic algorithms apply mechanisms such as Darwin's theory, namely natural evolution, to solve problems in several fields, especially engineering (Shopova et al., 2006). The essential keys of operation used in genetic algorithms go through the stages of reproduction, crossing, and mutation.

- Reproduction: Adds or scans individual strings according to their values. The fitness score is shown in the individual scoring process that has the same copy.
- Crossover: a method by selecting two chromosomes at random, and which usually comes from the parent so that they have or create new sources that will gather together in a new population (Shopova et al., 2006).
- Mutation: The process of making a new individual from a chromosome by changing the genes in it.

2.6 The Performance Index of ITAE

The performance index number used in this study is ITAE (integral of time multiplied absolute error), is a performance index that minimizes overshoot and dampens oscillations (Martins, 2005). The ITAE equation can be seen in Equation (4)(5).

$$ITAE = \int_{0}^{T} t\,|\,e(t)\,|\,dt \qquad (4)$$

$$e(t) = r(t) - y(t) \qquad (5)$$

Where e (t) is the difference or error, r (t) is the reference value, and y (t) is the measured value (Martins, 2005).

3. Methodology

3.1. FOPID Parameter Tuning Flowchart

The flowchart in Figure 3 explains how the FOPID parameter tuning works.

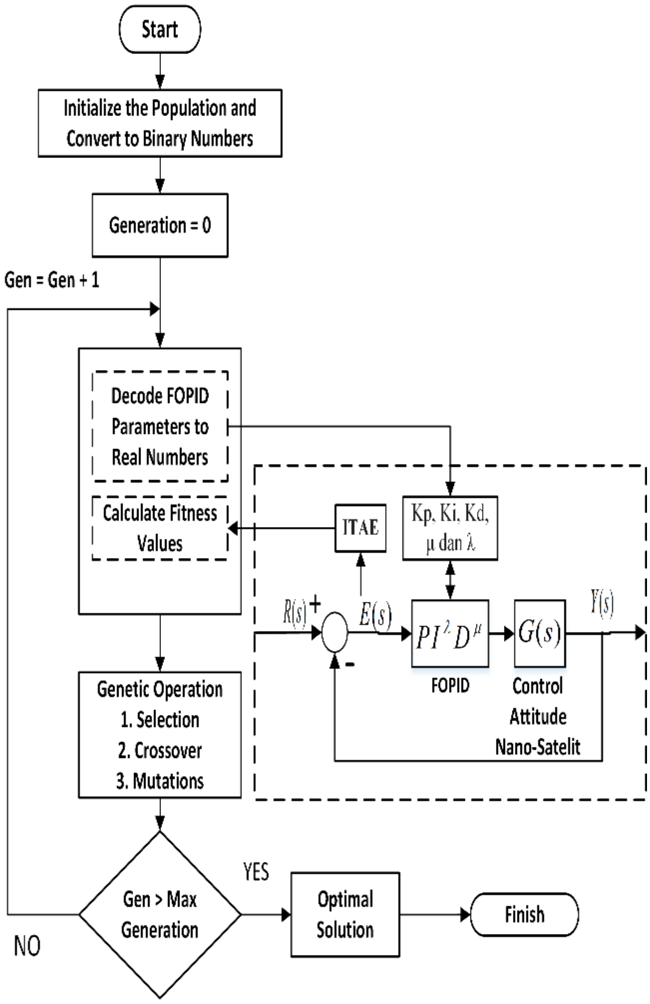

Figure 3. Flowchart of How FOPID Works with GA

In general, it can be explained that the process of tuning the FOPID parameters is almost the same between roll, pitch and yaw, only the initial input and the process after calculating the fitness values are different. The value of the plant equation for the three attitude control on nano-satellites is known as follows equation (6)(7)(8) (Mashor et al., 2018) :

$$\Phi_{(s)} = \frac{s^2 + 0.3051s + 0.2040}{s^4 + 1.1050s^2 + 0.1650} \tag{6}$$

$$\theta_{(s)} = \frac{1}{s^2 - 0.0071138} \tag{7}$$

$$\psi_{(s)} = \frac{s^2 - 0.3023s + 0.8088}{s^4 + 1.1050s^2 + 0.1650} \tag{8}$$

3.2. PID and FOPID Controller Parameters

Previous research has shown the search results for PID auto-tuning and manual tuning controller parameters (Mashor et al., 2018), the results of PID parameter tuning and the computational FOPID (GA) calculation on the roll, pitch, and yaw nano-satellite attitude control shown in Table 1, Table 2, and Table 3.

Table 1. The Value of PID and FOPID Control Parameters for Nano-Satellite Roll Attitude Control

Parameters	PID M-T	PID A-T	FOPID GA-ITAE
Kp	23	16.979	20.502
Ki	0.560	6.152	20.865
Kd	6	8.164	20.480
λ	1	1	1.022
μ	1	1	0.193

Table 2. The Value of PID and FOPID Control Parameters for Nano-Satellite Pitch Attitude Control

Parameters	PID M-T	PID A-T	FOPID GA-ITAE
Kp	18.500	0.152	15
Ki	0.040	0.006	15
Kd	4.350	0.833	15
λ	1	1	0.264
μ	1	1	0.758

Table 3. The Value of PID and FOPID Control Parameters for Nano-Satellite Yaw Attitude Control

Parameters	PID M-T	PID A-T	FOPID GA-ITAE
Kp	20	0	18
Ki	0.500	0.029	17.999
Kd	5	0	18
λ	1	1	0.003
μ	1	1	0.708

The search for FOPID GA parameters on the three control attitudes of the roll, pitch, and yaw nano-satellites used computation with MATLAB. The PID and FOPID parameter values are simulated in the form of steady response performance to determine the comparison.

3.3. Closed-Loop System for Attitude Control Nano-Satellite

The general block diagram of a closed-loop system for attitude control nano-satellite, wherein the FOPID controller is implemented on roll, pitch and yaw condition, is shown in Figure 4.

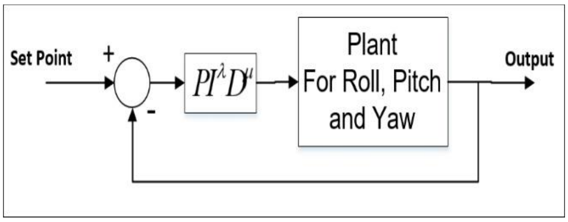

Figure 4. The Block Diagram of FOPID Controller for Nano-Satellite

The FOPID controller can be encapsulated into the time domain as

$$u(t) = K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^{\mu} e(t) \tag{9}$$

Next, we need to determine the parameter value of the FOPID controller to find out the final value. By multiplying these values by the initial nano-satellite plant, u (t) equation for each nano-satellite attitude control is shown in equations (10), (11) and (12).

$$u(t) = 20.5e(t) + 20.9D^{-1.02}e(t) + 20.5D^{0.19}e(t) \tag{10}$$

$$u(t) = 15e(t) + 15D^{-0.264}e(t) + 15D^{0.758}e(t) \tag{11}$$

$$u(t) = 18e(t) + 17.9D^{-0.003}e(t) + 18D^{0.708}e(t) \tag{12}$$

Then, it can be found that the transfer function produces the formula from the result of the substitution to the equation as :

$$U(s) = \frac{20.5s^{0.19} + 20.9s^{1.02} + 20.5}{s^{1.02}} \tag{13}$$

$$U(s) = \frac{15s^{0.758} + 15s^{0.264} + 15}{s^{0.264}} \tag{14}$$

$$U(s) = \frac{18s^{0.708} + 17.9s^{0.003} + 18}{s^{0.003}} \tag{15}$$

4. Results and Analysis

4.1 Steady Response Output Results

The results of steady response curves and control cues for PID auto-tuning, manual tuning and

FOPID types using genetic algorithms (GA) with ITAE criteria on nano-satellite roll attitude control can be seen in Figure 5, nano-satellite pitch attitude control in Figure 6 and attitude control yaw nano-satellite in Figure 7. The analysis results of the steady response curve of the three axes of roll, pitch and yaw attitude control show that the FOPID controller with genetic algorithm (GA) is better than the classical PID controller because it has very few insulating wave spikes and quickly reaches the desired steady-state value or the desired stability value. Furthermore, to clarify in more detail in finding which controller is better, a ranking system with the same weight is used.

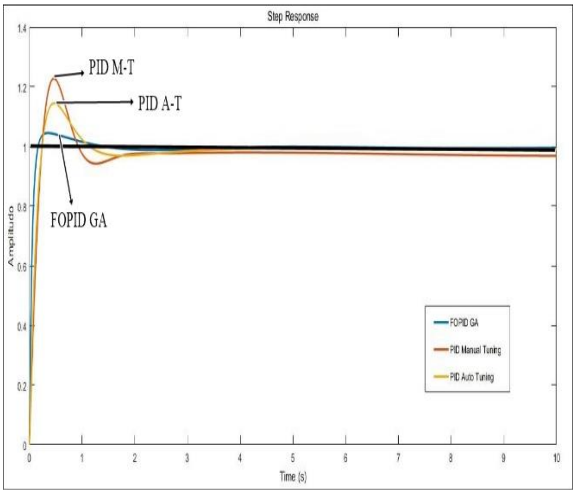

Figure 5. Steady Response Curves for PID and FOPID on Roll Attitude Control

Figure 4 shows the steady-state graph on the nano-satellite attitude control when roll, the FOPID controller with a genetic algorithm or FOPID GA has a better response than the PID autotuning controller or PID A-T and the manual tuning PID controller or PID M-T.

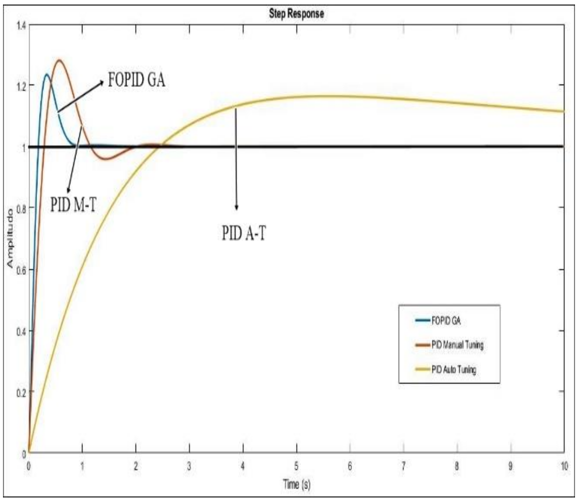

Figure 6. Steady Response Curves for PID and FOPID on Pitch Attitude Control

Figure 6 shows the steady-state graph in the nano-satellite attitude control at a pitch, the PID A-T controller looks very far to achieve stability values, and the FOPID GA controller is still better than the other controllers.

Based on Figure 7 shows a steady-state graph on the nano-satellite attitude control at yaw, the PID AT controller appears irregularly isolated if the time in the graph is extended and the FOPID GA controller is better in terms of speed to achieve stability values than PID MT, but PID MT is better in minimizing signal wave spikes.

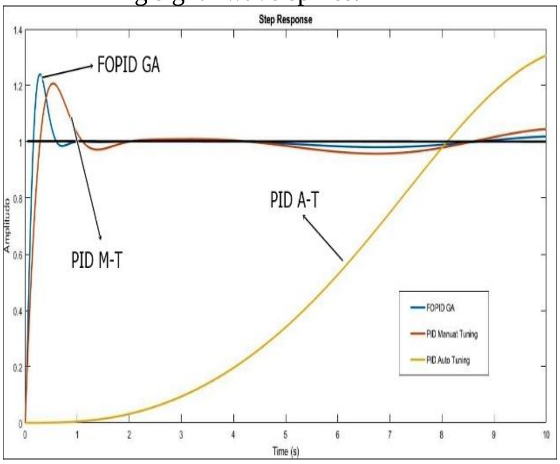

Figure 7. Steady Response Curves for PID and FOPID on Yaw Attitude Control

Overall, the FOPID GA controller value is smaller, meaning that it is better than other controllers. The order of ranking one for each parameter of the performance value is shown with a highlight. The results of the control signal response values for the types of PID and FOPID controllers in the roll, pitch and yaw nano-satellite attitude control can be seen in Table 4, Table 5 and Table 6.

In the roll attitude control, it can be seen that the three performance values of rise time, settling time, and overshoot have the best values on the FOPID GA control which have been highlighted in Table 4.

Table 4. Nano-Satellite Attitude Control Performance Parameters for PID and FOPID Controller with Roll Condition

Controllers	Rise Time (seconds)	Settling Time (seconds)	Overshoot (%)
PID A-T	0,174	2,029	15,588
PID M-T	0,175	1,434	26,759
FOPID GA	0,098	0,994	4,952

The pitch attitude control has the best value in the percent overshoot but the time to reach the stability value takes a long time for the PID auto-tuning controller (PID A-T). The FOPID controller with a genetic algorithm (FOPID GA) is still superior based on the rise time's performance and settling time values based on data from research shown in Table 5.

Table 5. Nano-Satellite Attitude Control Performance Parameters for PID and FOPID Controller with Pitch Condition

Controllers	Rise Time (seconds)	Settling Time (seconds)	Overshoot (%)
PID A-T	1,786	25,440	16,44
PID M-T	0,222	1,748	28,056
FOPID GA	0,134	0,741	23,495

In the yaw attitude control, several auto-tuning parameter values with the PID controller experience oscillations that cannot be measured with a predetermined reference vector with a time range of 10 seconds. The best value in terms of rise time and settling time of the FOPID controller uses a genetic algorithm that is superior to other controllers even though in terms of overshoot it still experiences a slightly higher spike compared to PID controllers with manual tuning based on data from computational calculations shown in Table 6.

Table 6. Nano-Satellite Attitude Control Performance Parameters for PID and FOPID Controller with Yaw Condition

Controllers	Rise Time (seconds)	Settling Time (seconds)	Overshoot (%)
PID A-T	5,574	~	~
PID M-T	0,235	9,196	15,530
FOPID GA	0,121	8,567	21,806

5. Conclusion and Recommendations

The FOPID controller's performance with ITAE criteria in the genetic algorithm (GA) method for control of roll, pitch, and yaw attitudes on nano-satellites has better performance in the form of a few waves of isolation waves. It is faster in reaching steady-state values than the classical PID method. Using the genetic algorithm (GA) method to find the best value for the FOPID controller parameter proportional constant (Kp), integral constant (Ki), derivative constant (Kd), mu at the power of the fraction of the derivative (μ) and lambda at the power of the integral fraction (λ) so that superior in terms of rise time and settling time faster than PID controllers based on auto-tuning and manual tuning (Mashor et al., 2018) in previous studies. From these results, the nano-satellite attitude control values during roll with a rise time of 0098 seconds, settling time of 0.994 seconds and overshoot of 4.952, control of nano-satellite attitudes during an optimal pitch at rise time 0.134 seconds and settling time of 0.741 seconds later, nano-attitude control satellites when yaw at a rise time of 0.121 seconds and settling time 8,567 seconds.

The use of numerical computation methods such as genetic algorithms (GA) used in this study requires a long computation process with a large number of iterations so that the results found are optimal. Based on the development of a computer's design and performance, which is very rapidly developing at this time, other computational methods may emerge besides metaheuristic, which can support the calculation process of new computational methods so that they can be implemented in subsequent studies.

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