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PID tuning approaches for quadrotors unmanned aerial vehicles

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PID tuning approaches for quadrotors unmanned aerial vehicles

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Abstract. In this paper, a comparative study between different PID tunning techniques is presented. The proposed techniques are applied to solve the formation configuration problem for a cooperative team of unmanned vehicles. The formation problem for the cooperative team is divided into two levels of control, one is the backstepping control technique for the stabilization of the team members positions as a higher controller. Simultaneously, PID controller receives the desired position to stabilize the attitude control as a lower controller to track the desired planning trajectories. The main contribution of this paper is the comparison between the different control approaches in tunning the PID gains to stabilize attitude control for the leader quadrotor. Simulation results present the assessment of the proposed PID control technique compared with different PID tuning approaches such as local optimal control, fraction order, Ziegler–Nichols and genetic algorithm. Moreover, disturbance rejection and white noise attenuation criterions are inspected to evaluate the ability of the proposed controllers to preserve the stability of the system.

1. Introduction

In past few decades, unmanned aerial vehicles (UAVs) have become much popular and attracted more interest from scientist and researchers due to their potential use in military and civilian utilizations [1]. Nowadays, the vertical take-off and landing (VTOL) with four-rotors aircraft called quadrotor is considered as one of the most important UAVs. This sort of airplanes is characterized with unrevealed useful features such as small size, ultimate maneuverability capabilities, simplicity of design, and control. Quadrotor has the footprint of taking-off vertically from any place and landing vertically at any place regardless the hardness of that places. Quadrotors UAVs have the advantage of being able to accomplish specific and difficult tasks that cannot be done by fixed-wing aircrafts due to its unique characteristics.

There are various space applications where this capacity would be desired, for example, discharging raised territories and transporting merchandise to regions where street arrival isn't accessible. VTOL planes also provide direct entry to buildings or zones making them a quick type of transportation between regions, particularly those which are raised or have restricted admittance [2].

Conventionally, quadrotors usage is increased rapidly in the aerospace industry. It is fact that most of the usual payloads could be lifted using one or two rotors. However, Quadrotors have unique features that make it appealing. Naturally, one of these features is the higher and diverse capability for payload. The plainness of their control system is also an advantage; just by modifying the speed of every rotor separately.

The quadrotor is a vastly nonlinear, multi-variables, strongly coupled, under-actuated, sensitive to interference and essentially an unstable system (6 DOF, 3 translational and 3 rotational motions, with only 4 actuators), which acts as fundamental foundation for design of control plan. This makes control design is very challenging. currently, there are numerous methods to control the quadrotor, the literature [3], [4], [5], [6], and [7] respectively focused on PID, sliding mode, backstepping, fuzzy neural network, and H-infinity approaches. The adaptive neuro-fuzzy inference system (ANFIS) controller to the quadrotors is discussed in [8] and [9].

It is believed that multiple cooperative quadrotors are more stable and adaptable to fulfill the desired demands than single quadrotor [10]. Unmistakably, the general ability of the cooperative quadrotors can upgrade execution, essential time range, task allocation, system proficiency and the safety to accomplish the desired tasks. Complex tasks cannot be achieved efficiently by a single quadrotor, such as finding objects in massive areas like in searching and relief missions, basic payloads restrictions, etc. Because of these regards, collaboration of numerous UAVs has recently gotten a lot of consideration from the scientist and researchers [11]. Quick advancements on computers, actuators, sensors fusion, and communications technologies have all an impact in developing the novel epoch of collaboration methodologies for cooperative quadrotors.

State of art of the proposed controller designed based on combining couple of robust controllers that can deal with highly non-linear systems effectively [10]. The proposed controller is divided into couple of parts working together. Backstepping (BS) controller is used to stabilize the position control as a higher controller. Simultaneously, PID controller receives the desired position to stabilize the attitude control as a lower controller to track the desired planning trajectories.

The main contribution of this paper is using Local Optimal Control (LOC), and Fractional Order PID (FOPID) approach combined with backstepping controller in the proposed cascaded controller for first time in cooperative quadrotors. LOC and FOPID are used to tune PID gains to stabilize attitude control for cooperative quadrotors.

BS controller is used mostly as a higher controller [12]. BS controller is an effective control strategy for extremely nonlinear frameworks [13]. There are many benefits of utilizing BS controller such as rapid convergence rate, stability, capability to manage nonlinear frameworks using recursive operation of Lyapunov function, robustness regardless presence of uncertainties, and simplicity [5].

Multivariate control systems were given much attention because of the growing complexity of control systems operations [14].

Numerous researchers are broadly utilizing fractional order control (FOC) to accomplish better robust performance in several control systems. FOC approach has accomplished further remarkable outcomes on quadrotors particularly enhancing the stability of its frameworks.

The superiority of fractional order can be demonstrated in the ability of fractional calculus to configure the gain margin and the phase margin in the frequency domain of the quadrotor framework freely. Fractional order PID (FOPID) is developed based on FOC theory and traditional PID theory. This controller expands the resolution of tuning parameters from the triple parameters of PID,$(k_P, k_I, K_D)$and to five parameters by adding the FOC parameters λ and μ.

LOC is convenient for controlling non-linear systems with multivariable parameters as Single Input Single Output (SISO) systems [15]. LOC is characterized as well with robust performance. The proposed BS-PID controller enhanced the overall performance and stability of the underlying cooperative quadrotors system.

This paper is organized as follows:

Section 2 presents a short description and mathematical model of the quadrotor. The controller's approach is described in section 3. Section 4 shows the simulation results of trajectory tracking using the proposed controllers. Finally, conclusion is introduced at final section in section 5.

2. Quadrotor control approaches

2.1. Backstepping control design

BS approach design has been formerly studied in [13]. BS approach is a preferred control technique over various approaches. The controller utilizes a recursive algorithm, where the controller has divided its mechanism into several steps guaranteeing the stability of each step gradually. The inputs of BS controller are directly received as a desired mission plan and a streaming of information sent by the onboard quadrotor sensors. BS utilizes numerous coefficients during the computation. These coefficients represent the quadrotor dynamics and states. The yield of the controller approach is the separately sent pulse width modulation (PWM) signal for every rotor of the quadruple rotors.

The proposed controller utilizes BS in the higher control loop of positioning the underlying framework, so, BS is responsible of defining the updated positions of every quadrotors of the cooperative squad. The altitude control and the position control for i^{th} quadrotors (U_{1i}, u_{xi}, u_{yi}) is assumed as:

$$\begin{aligned} U_{1i} &= \frac{m_i}{\cos x_{1i} \cos x_{3i}} (g_i + g_{7i} - \alpha_{7i}(g_{8i} + \alpha_{7i} g_{7i}) - \alpha_{8i} g_{8i}) \\ u_{xi} &= \frac{m_i}{U_{1i}} (g_{9i} - \alpha_{9i}(g_{10i} + \alpha_{9i} g_{9i}) - \alpha_{10i} g_{10i}) \\ u_{yi} &= \frac{m_i}{U_{1i}} (g_{11i} - \alpha_{11i}(g_{12i} + \alpha_{11i} g_{11i}) - \alpha_{12i} g_{12i}) \end{aligned} \tag{1}$$

2.2. PID Control Design

PID controllers is considered as an ordinary controller. PID is generally used because of design simplicity and reduced number of tunable parameters in the production controlled systems [16], and [17]. Upwards of 90 percent of the commonly deployed controllers are routinely based on PID controllers. PID controller is designed in the proposed controller as a lower controller to control the attitude channels of each member of cooperative quadrotors. The popular mathematical equation of PID controller is formed as [18]:

$$u(t) = K_P + K_I \int_0^t e(t)dt + K_D \frac{d}{dt} e(t) \tag{2}$$

A scheme block diagram for PID controller is depicted in Figure 1.

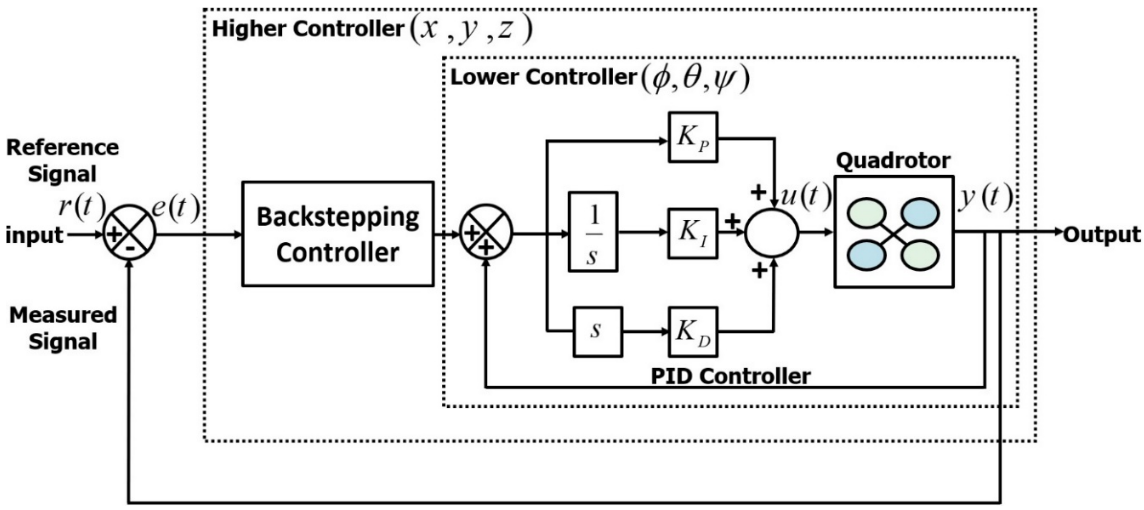

Figure 1. A scheme block diagram for proposed PID controller.

The quadrotor model should be reduced in order to make a simple reverse model to be invoked in the control techniques. That can be done by removing gyroscopic terms from the dynamic equations [19]. So, the simplified mathematical equation can be reformulated as:

$$\begin{pmatrix} \ddot{x}_{1i} \\ \ddot{x}_{3i} \\ \ddot{x}_{5i} \end{pmatrix} = \begin{pmatrix} \ddot{\phi}_i \\ \ddot{\theta}_i \\ \ddot{\psi}_i \end{pmatrix} = \begin{pmatrix} \frac{l_i}{I_{xxi}} U_{2i} \\ \frac{l_i}{I_{yyi}} U_{3i} \\ \frac{1}{I_{zzi}} U_{4i} \end{pmatrix} \tag{3}$$

Converting (3) to Laplace model and adding the rotor dynamics yields:

$$\begin{cases} \phi_i(s) = \frac{B_i^2 b_i l_i}{s^2 (s+A_i)^2 I_{xxi}} \left(u_{4i}^2(s) - u_{2i}^2(s) \right) \\ \theta_i(s) = \frac{B_i^2 b_i l_i}{s^2 (s+A_i)^2 I_{yyi}} \left(u_{3i}^2(s) - u_{1i}^2(s) \right) \\ \psi_i(s) = \frac{A_i^2}{s^2 (s+A_i)^2 I_{zzi}} \sum_{n=1}^{4} (-1)^{n+1} u_{ni}^2(s) \end{cases} \tag{4}$$

where, the parameters A_i and B_i symbolize the rotor dynamics.
Inserting the control inputs instead of the motor inputs in (4) yields:

$$\begin{cases} \phi_i(s) = \frac{A_i^2 l_i}{s^2 (s+A_i)^2 I_{xxi}} U_{2i} \\ \theta_i(s) = \frac{A_i^2 l_i}{s^2 (s+A_i)^2 I_{yyi}} U_{3i} \\ \psi_i(s) = \frac{A_i^2}{s^2 (s+A_i)^2 I_{zzi}} U_{4i} \end{cases} \tag{5}$$

Assume that the required angles are $x_{2i} = \dot{\phi}_i, x_{4i} = \dot{\theta}_i, x_{6i} = \dot{\psi}_i$, and $x_{1id} = x_{3id} = x_{5id} = 0$ if the state is hovering. So, the controller formulas can lastly be acquired as:

$$\begin{cases} U_{2i} = \frac{1}{b_{1i}} (K_{2i} x_{2i} - a_{1i} x_{4i} x_{6i}) + w_{2i} (x_{1id} - x_{1i}) \\ U_{3i} = \frac{1}{b_{2i}} (K_{3i} x_{4i} - a_{3i} x_{2i} x_{6i}) + w_{3i} (x_{3id} - x_{3i}) \\ U_{4i} = \frac{1}{b_{3i}} (K_{4i} x_{6i} - a_{5i} x_{4i} x_{6i}) + w_{4i} (x_{5id} - x_{5i}) \end{cases} \tag{6}$$

Various tuning approaches for PD and PID controllers are utilized to improve the overall performance and stability of the underlying cooperative quadrotors frameworks.

These tuning approaches are characterized with implementation simplicity and short execution time to exert the controller coefficients as inputs for the actuators.

2.2.1. Tuning PID Controller via Genetic Algorithm
GA tuning approach is characterized with its feature to be easily and promptly executed. Choice the proper estimations of the controller parameters still an essential challenge in designing the proposed PID controllers $(K_{2i}, w_{2i}), (K_{3i}, w_{3i}), (K_{4i}, w_{4i})$. However, creating the population based on choosing reasonable GA chromosomes is the first and most critical stage. Every chromosome involves the triple PID parameters K_P, K_I, K_D with esteem limits differed rely upon the utilized objective functions and the delay.

At first, Simplex Optimization (SO) approach is utilized to obtain the ideal estimations of these controller parameters as rudimentary satisfactory parameters for GA. Then, GA acquire a fine tuning of the proposed PID parameters based on hypothetical evolutionary technique that parallels the real biology in the world. The parents' choice and genes conjunction to produce post-generation (crossover) is used as a major GA procedure. The genetic algorithm is designed to lessen multi-objective operation. This operation decreases the mean square error (MSE) amongst inputs and outputs of the system [18]. The resultant values for control parameters generated by GA are revealed in Table 1.

Table 1. **Genetic Algorithm** Controller **parameters.**

Population size	Crossover	Number of generations
200	0.8	800

The controller design strategy is devoted to the purpose of performance optimization of a specific system or subsystem [20]. The purpose of the proposed optimization technique is to achieve the stability efficiency for the cooperative quadrotors, speed up the response, and reducing overshoots as least as could be expected.

A PD controller is developed as a lower control for the underlying cooperative quadrotors for attitude and altitude channels as in (7):

$$U_{2i,3i,4i} = K_{pi_{\phi_i,\theta_i,\psi_i}}(\phi_i, \theta_i, \psi_i) + K_{Di_{\phi_i,\theta_i,\psi_i}}(\dot{\phi}_i, \dot{\theta}_i, \dot{\psi}_i) \tag{7}$$

The forthcoming control formula is utilized to obtain the required conduct of the altitude channel for the vertical location:

$$u_{1i} = \frac{r_{1i} + m_i g}{\cos\phi_i \cos\theta_i} \tag{8}$$

$$r_{1i} = -a_{1i}\dot{z}_i - a_{2i}(z_i - z_{id}) \tag{9}$$

The required altitude z_d can be determined by:

$$z_{id} = \frac{-a_{1i}\dot{z}_i - a_{2i}z_i - r_{1i}}{a_{2i}} \tag{10}$$

Where a_{1i} and a_{2i} symbolize K_{Di} and K_{pi} respectively. Considering the uncertainties and hardware constraints; the controller coefficients has been determined as demonstrated in Table 2:

Table 2. **PD controller** coefficients **tuned by GA.**

Controller Gain	Roll	Pitch	Yaw	Altitude
K_{Pi}	-14.6211	-46.6211	-64	4.7673
K_{Di}	48.7832	112.7832	42.2144	4.9794

Verifying the proposed control rule is achieved by many simulation experiments. Even with extreme initial states in the attitude channels, the controller completed multiple simulation situations successfully.

2.2.2. Tuning PID Controller via Ziegler-Nichols

Ziegler-Nichols approach is one of the most popular techniques in tuning PID parameters in less time [21]. Ziegler and Nichols created rules for configuring the PID gains. There are couple of techniques to tune the PID parameters using ZN. One of them dependent on open-loop technique. However, the other technique dependent on closed-loop technique. Closed-loop technique is utilized, in this paper, to regulate the gains of the PD parameters. Table 3. summarized the PD controller coefficients tuned by ZN as follow.

Table 3. **PD controller** coefficients **tuned by ZN.**

Controller Gain	Roll	Pitch	Yaw	Altitude
K_{Pi}	44.32	-50.62	42.21	21.69
K_{Di}	-9.787	52.78	-64	15.72

2.2.3. Tuning PID Controller via Fractional Order

The BS-PID tuned by FOPID controller is divided into couple of parts working together. Backstepping controller is used to stabilize the position control as a higher controller. Simultaneously, PID tuned by FOPID controller receives the desired position to stabilize the attitude control as a lower controller to track the desired planning trajectories as depicted in Figure 2.

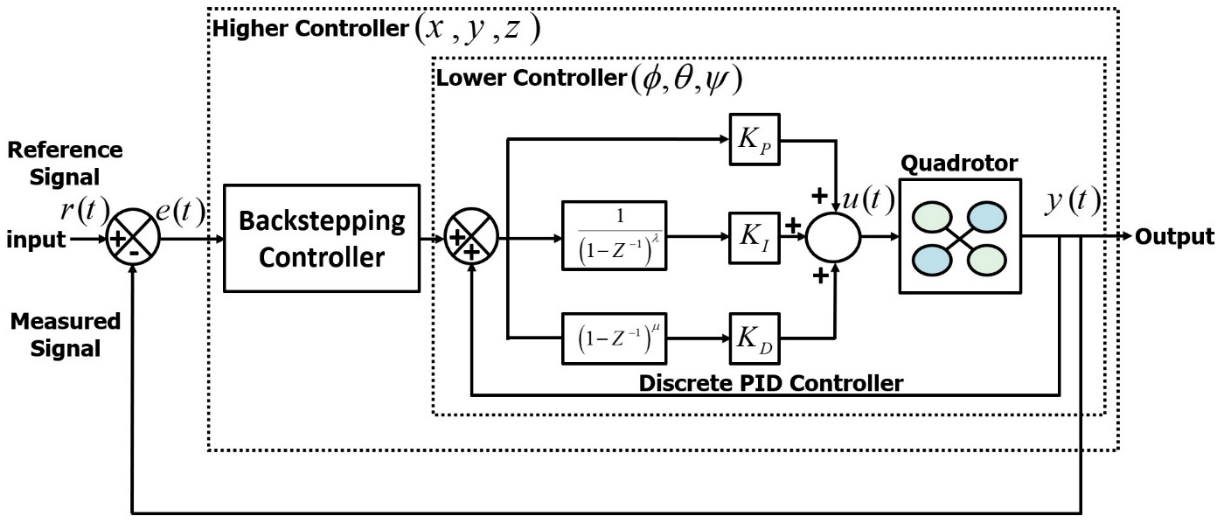

Figure 2. FOPID block diagram for 2nd order model of quadrotor framework

The general form of digital PID controller for i^{th} quadrotor can be defined as [15]:

$$G_i(z) = \frac{u_i(z)}{e_i(z)} = K_{Pi} + \frac{K_{Ii}}{1-z^{-1}} + K_{Di}(1-z^{-1}) \tag{11}$$

By multiplying equation (11) with $(1-z^{-1})$:

$$(1-z^{-1})u_i(z)=K_{Pi}e_i(z)(1-z^{-1})+K_{Ii}e_i(z)+K_{Di}e_i(z)(1-z^{-1})^2 \quad (12)$$

$$u_i(z)-u_i(z)z^{-1}=K_{Pi}(e_i(z)-e_i(z)z^{-1})+K_{Ii}e_i(z)+K_{Di}(e_i(z)-2e_i(z)^{-1}-e_i(z)z^{-2}) \quad (13)$$

Suppose that $u(nT)$ as a discrete time, and use it in (13):

$$u_i(n)-u_i(n-1)=K_{Pi}\left(e_i(n)-(e_i(n-1)\right)+K_{Ii}e_i(n)+K_{Di}\left(e_i(n)-2e_i(n-1)+e_n(n-2)\right) \quad (14)$$

So, the digital form of fractional order $PI^{\lambda}D^{\mu}$ is formulated by:

$$G_i(z)=\frac{u_i(z)}{e_i(z)}=K_{Pi}+K_{Ii}\frac{(1+z^{-1})}{(1-z^{-1})}\sum_{m=0}^{\infty}f_{mi}(1-\lambda_i)z^{-m}+K_{Di}\sum_{m=0}^{\infty}f_{mi}(\mu_i)z^{-m} \quad (15)$$

The digital form of fractional order $PI^{\lambda}D^{\mu}$ is reformulated for R^{th} order by:

$$G_i(z)=\frac{u_i(z)}{e_i(z)}=K_{Pi}+K_{Ii}\frac{(1+z^{-1})}{(1-z^{-1})}\sum_{m=0}^{R}f_{mi}(1-\lambda_i)z^{-m}+K_{Di}\sum_{m=0}^{R}f_{mi}(\mu_i)z^{-m} \quad (16)$$

The estimation of R order of the system should be chosen carefully respecting the utilized hardware limitation to satisfy the desired requirement without wasting memory in unnecessary bigger calculations with increasing of the supposed order [22].

The general form of fractional order $PI^{\lambda}D^{\mu}$ for i^{th} quadrotor is formulated by:

$$G_i(z)=\frac{u_i(z)}{e_i(z)}=K_{Pi}+\frac{K_{Ii}}{S^{\lambda_i}}+K_{Di}S^{\mu_i} \quad (17)$$

where the tunable parameters of FOC λ_i and $\mu_i \geq 0$.

The time domain differential form of fractional order $PI^{\lambda}D^{\mu}$ can be formulated as [23]:

$$u_i(t)=K_{Pi}e_i(t)+K_{Ii}D_t^{-\lambda_i}e_i(t)+K_{Di}D_t^{-\mu_i}e_i(t) \quad (18)$$

The block diagram of fractional order $PI^{\lambda}D^{\mu}$ can be shown in Figure 3.

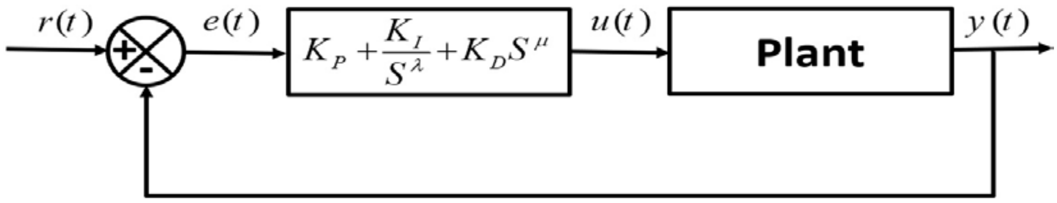

Figure 3. The block diagram of fractional order $PI^{\lambda}D^{\mu}$

The PID approach coefficients tuned by FOPID are summarized in Table 4.

Table 4. PID controller coefficients tuned by FOPID

Controller Gain	Roll	Pitch	Yaw
K_{Pi}	27.32	7.429	24.24
K_{Ii}	4.41	1.126	11.56
K_{Di}	0.73	2.85	15.86
λ_i	0.06	-0.72	0.15
μ_i	0.62	0.97	0.75

2.2.4. Tuning PID Controller via Local Optimal Control

LOC is used to tune PID gains in the planned cascaded controller to stabilize attitude control for cooperative quadrotors.

Figure 3 depicts a block diagram for the underlying platform using digital PID controller.

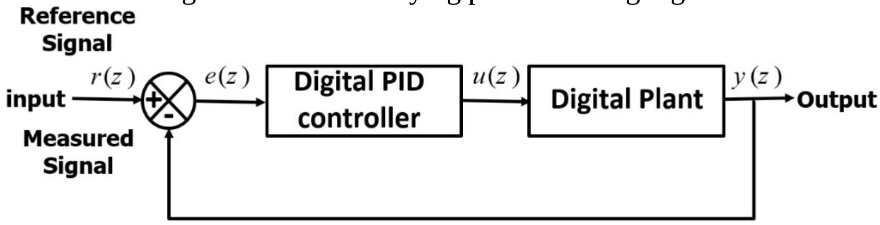

Figure 4. Digital PID controller schematic diagram.

The error in relation to the controller inputs and outputs can be defined as:

$$e_i(z) = r_i(z) - y_i(z) \tag{19}$$

The general form of digital PID approach is definable as [15]:

$$G_i(z) = \frac{u_i(z)}{e_i(z)} = K_{Pi} + \frac{K_{Ii}}{1-z^{-1}} + K_{Di}(1-z^{-1}) \tag{20}$$

$\delta u_i(n)$ is acquired by as:

$$\delta u_i(n) = u_i(n) - u_i(n-1) \tag{21}$$

From (20; $\delta u_i(n)$ is obtained by:

$$\delta u_i(n) = \left(K_{Pi} + K_{Ii} + K_{Di}\right)e_i(n) - \left(K_{Pi} + 2K_{Di}\right)e_i(n-1) + K_{Di}e_i(n-2) \tag{22}$$

The transfer function to regulate digital PID approach coefficients utilizing LOC is formed by:

$$G_i(z) = \frac{y_i(z)}{u_i(z)} = \frac{\beta_i z}{z^2 + \alpha_{1i} z + \alpha_{2i}} \tag{23}$$

α_{1i} , α_{2i} and β_i are the coefficients at the second order form of the linearized transfer function.

So, the system model can be represented as:

$$y_i(n) = \alpha_{1i} y_i(n-1) + \alpha_{2i} y_i(n-2) + \beta_i u_i(n-1) \tag{24}$$

Figure 4. depicts LOC block diagram.

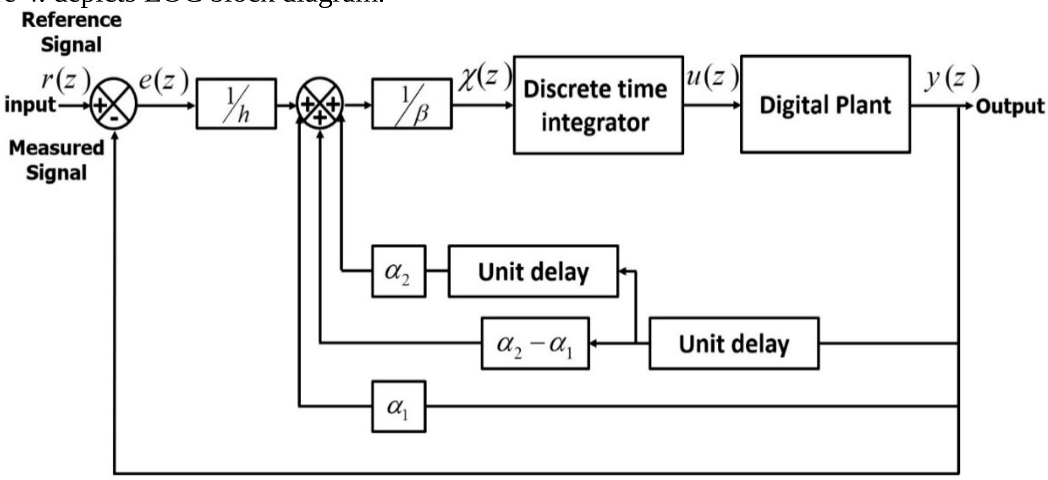

Figure 5. **LOC block diagram for 2nd** order **model.**

The error is obtained by:

$$e_i(n) = r_i(n) - y_i(n) \tag{25}$$

$\chi_i(n)$ can be obtained by:

$$\chi_i(n) = \frac{1}{b_i}\left[\frac{1}{h_i}e_i(n) + \alpha_{1i}y_i(n) + (\alpha_{2i} - \alpha_{1i})y_i(n-1) + \alpha_{2i}y_i(n-2)\right] \tag{26}$$

In step input case represented by $r_i(n)$:

$$r_i(n) = r_i(n-1) = r_i(n-2) \tag{27}$$

So, $\chi_i(n)$ can be obtained by:

$$\chi_i(n) = \frac{1}{\beta_i}\left[\frac{1}{h_i}e_i(n) + \alpha_{1i}y(n) + (\alpha_{2i} - \alpha_{1i})y_i(n-1) + \alpha_{2i}y_i(n-2) + \alpha_{1i}r_i(n-1) - \alpha_{1i}r_i(n)\alpha_{2i}r(n-2) - \alpha_{2i}r_i(n-1)\right] \tag{28}$$

From (26) and (27):

$$\chi_i(n) = \frac{1}{\beta_i}\left[\frac{1}{h_i}e_i(n) + \alpha_{1i}e(n) - (\alpha_{2i} - \alpha_{1i})e_i(n-1) + \alpha_{2i}e_i(n-2)\right] \tag{29}$$

Assuming τ_{si} as a time sample; $u_i(z)$ can be obtained by:

$$u_i(z) = \frac{\tau_{si}}{1 - z^{-1}} \tag{30}$$

Assuming that:

$$\delta u_i(n) = \tau_{si}\chi_i(n) \tag{31}$$

Substituting (31) in (29) yields:

$$\delta u_i(i) = \frac{\tau_{si}}{\beta_i}\left[\frac{1}{h_i}e_i(n) + \alpha_{1i}e_i(n) - (\alpha_{2i} - \alpha_{1i})e_i(n-1) + \alpha_{2i}e_i(n-2)\right] \tag{32}$$

By equalizing coefficients $e_i(n)$, $e_i(n-1)$, $e_i(n-2)$ with (22) and (32) yields:

$$K_{Pi} + K_{Ii} + K_{Di} = \frac{\tau_{si}}{\beta_i h_i} - \frac{\alpha_{1i}\tau_{si}}{\beta_i} \tag{33}$$

$$K_{Pi} + 2K_{Di} = \frac{(\alpha_{2i} - \alpha_{1i})\tau_{si}}{\beta_i} \tag{34}$$

$$K_{Di} = \frac{\alpha_{2i}\tau_{si}}{\beta_i} \tag{35}$$

From (33), (34), and (35); LOC coefficients for the digital PID can be obtained as:

$$K_{Pi} = \frac{-\tau_{si}(\alpha_{1i} + \alpha_{2i})}{\beta_i} \tag{36}$$

$$K_{Ii} = \frac{\tau_{si}}{\beta_i h_i} \tag{37}$$

$$K_{Di} = \frac{\alpha_{2i}\tau_{si}}{\beta_i} \tag{38}$$

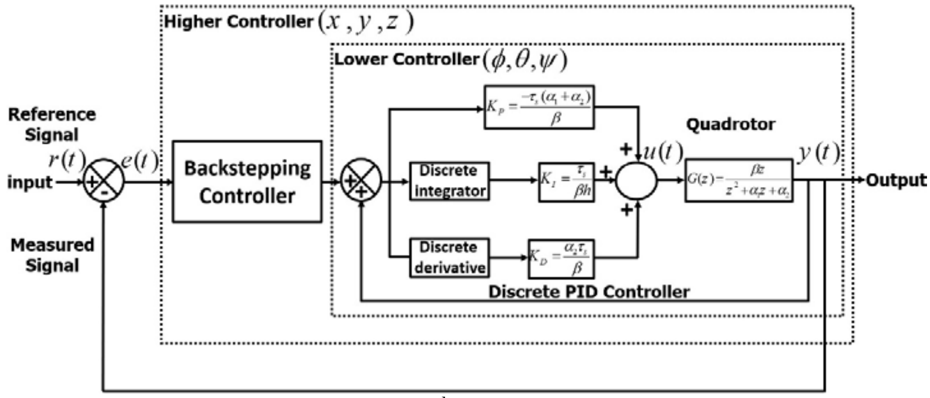

Figure 6. LOC block diagram for 2nd order model of quadrotor framework

PID coefficients tuned by LOC are dependent upon controller coefficients values and optimizable coefficient h_i. Figure 5. depicts PID approach coefficients of (36), (37), and (38) that utilized to optimize the 2nd order transfer function in (23).

From (11), the transfer function of Roll control is formed as:

$$G_i(z) = \frac{0.0002268z}{z^2 - 9.0329z + 2.8367} \tag{39}$$

The transfer function of Pitch control is formed as:

$$G_i(z) = \frac{0.0000533z}{z^2 - 1.355z + 0.39125} \tag{40}$$

The transfer function of Yaw control is formed as:

$$G_i(z) = \frac{0.0000865z}{z^2 - 2.5z + 0.5} \tag{41}$$

The PID controller coefficients tuned by LOC are summarized in in Table 3.

Table 5. PID controller coefficients tuned by LOC.

Controller Gain	Roll	Pitch	Yaw
K_{Pi}	27.32	18.08	23.12
K_{Ii}	4.41	18.76	11.56
K_{Di}	12.51	7.34	5.78

3. Simulation results and comparative study

Several simulations trials on MATLAB Simulink are performed using the entire quadrotor model to modulate the coefficients of the proposed controllers. The functions of the controllers are tested in stabilizing the orientation angles in the lower control loop to any of quadrotor of the underlying cooperative quadrotors. The isolating ranges among the cooperative quadrotors and speed are obliged at control approaches to keep the planned formation configuration. The comparative criterion between the offered controllers includes designed trajectory tracking, wind disturbance rejection, and noise cancellation.

3.1. Free flight scenario:

The underlying cooperative quadrotors team is examined in trajectory tracking in ideal case of free flight. The study of the tunning approaches is applied on the leader quadrotor, however the results on applying the tunning approaches on the other team members fulfill the desired formation requirements.

Figures 4-7 display the trajectory tracking of leader quadrotor controlled by BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA, and in altitude and attitude (roll, pitch, and yaw) orientations respectively.

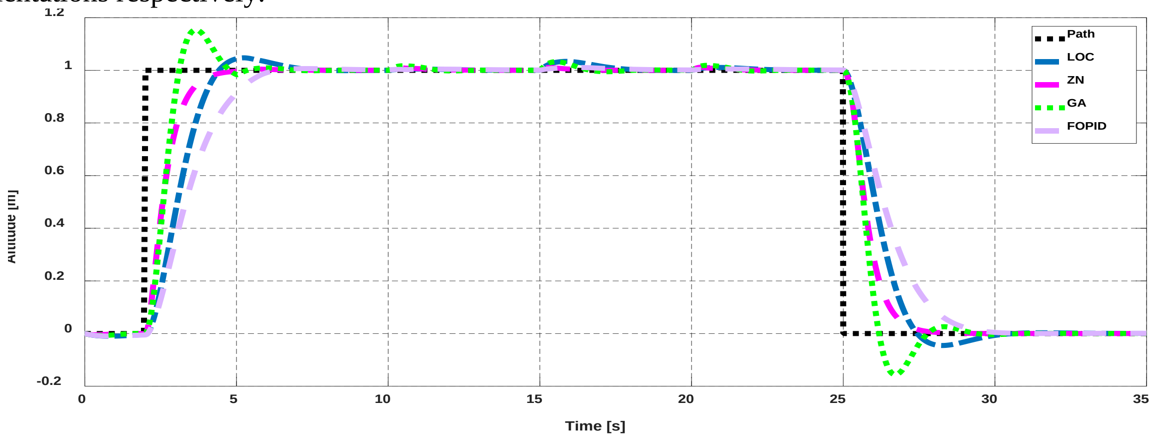

Figure 7. Trajectory tracking of BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA for a single quadrotor in ***Z***-orientation.

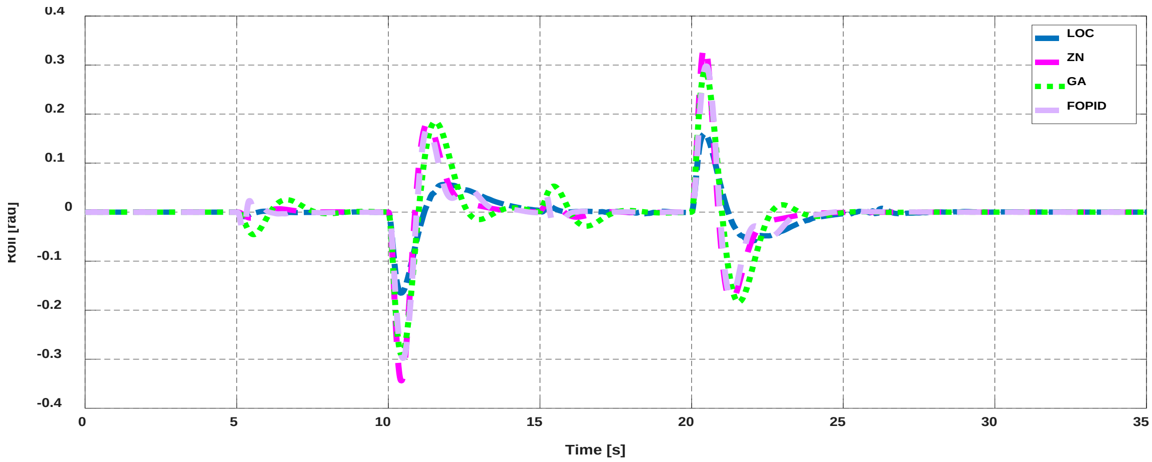

Figure 8. Roll control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA.

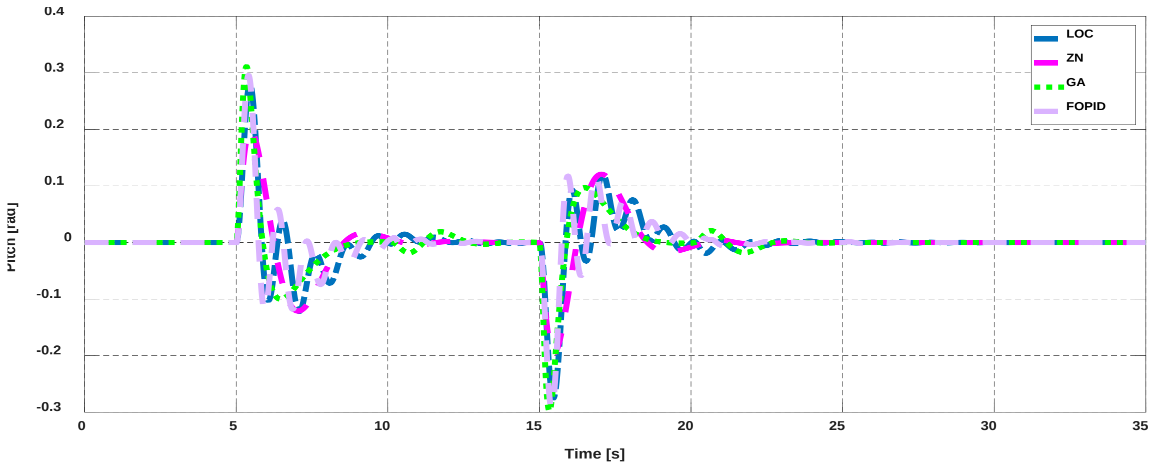

Figure 9. Pitch control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA.

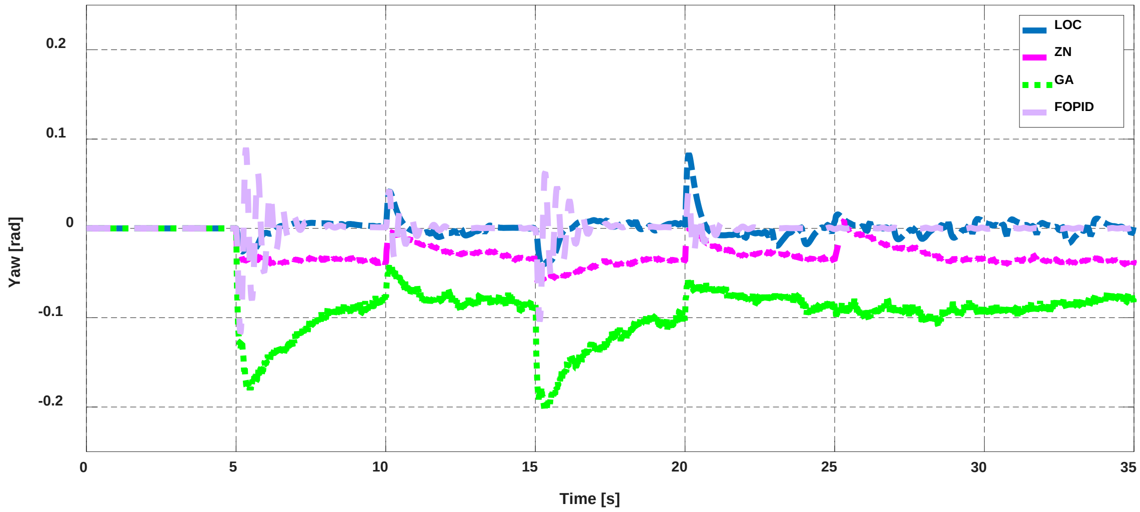

Figure 10. Yaw control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA.

Figures 4-7 show successful of the trajectory tracking of a single quadrotor from the underlying cooperative quadrotors controlled by BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA, and in altitude and attitude orientations respectively. The obtained trajectory of each approach is compared with other approaches. The analysis of the acquired results indicated that the output response of FOPID method is better than that of BS-PD tuned by ZN and GA.

3.2. Wind disturbance rejection and noise attenuation:

Stability and robustness evaluation of BS-PID controller tuned by LOC, FOPID and BS-PD controllers tuned by ZN and GA is realized. These controllers are studied and compared in view of stability scope based on the ability of these controllers on disturbance rejection and noise cancelation.

Figures 8-11 display the trajectory tracking of single quadrotor controlled by BS-PID controller tuned by LOC, FOPID and BS-PD controllers tuned by ZN and GA under effect of wind disturbance in altitude and attitude orientations, respectively.

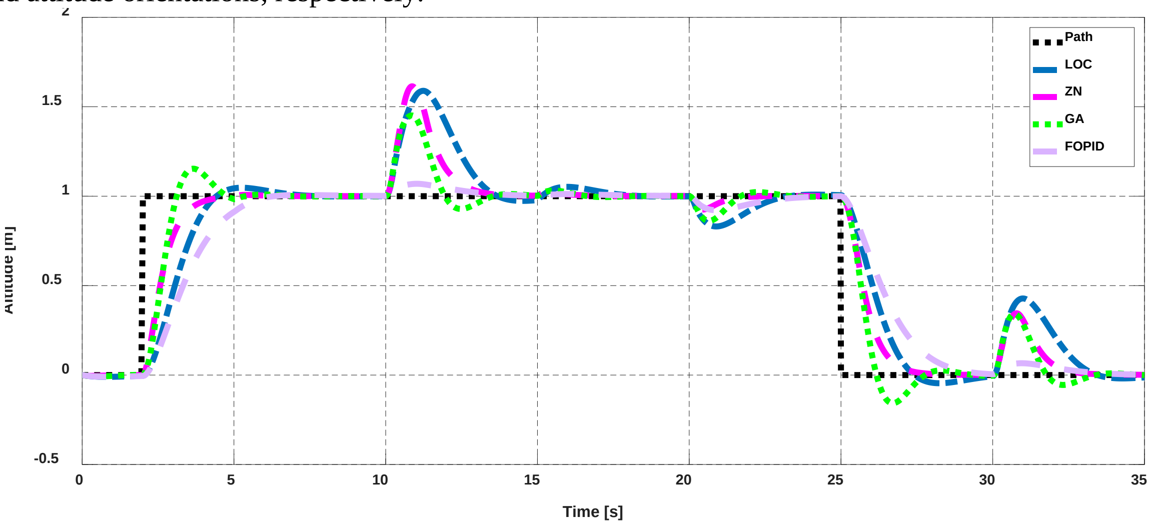

Figure 11. Trajectory tracking of BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA for a single quadrotor in ***Z***-orientation under effect of wind disturbance.

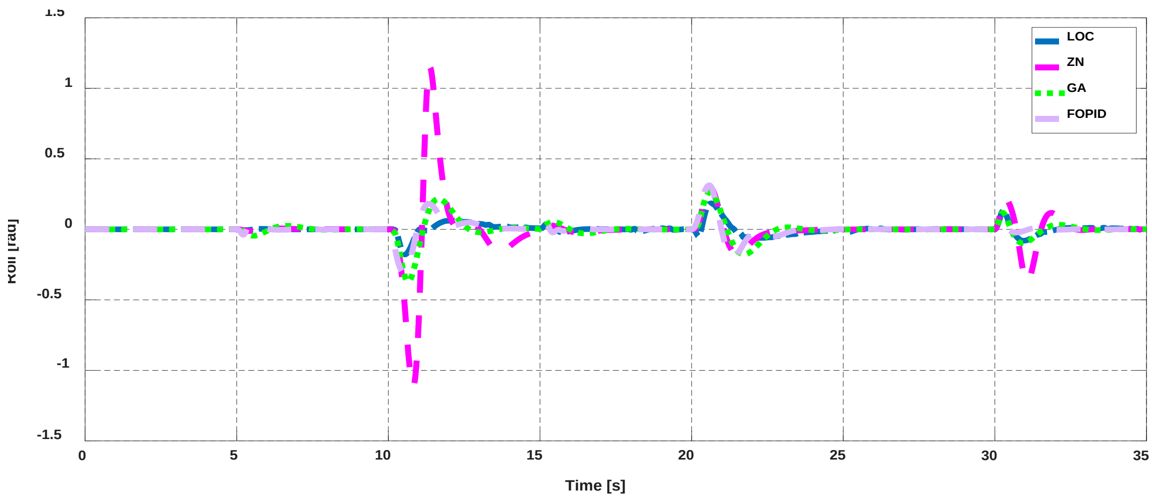

Figure 12. Roll control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA under effect of wind disturbance.

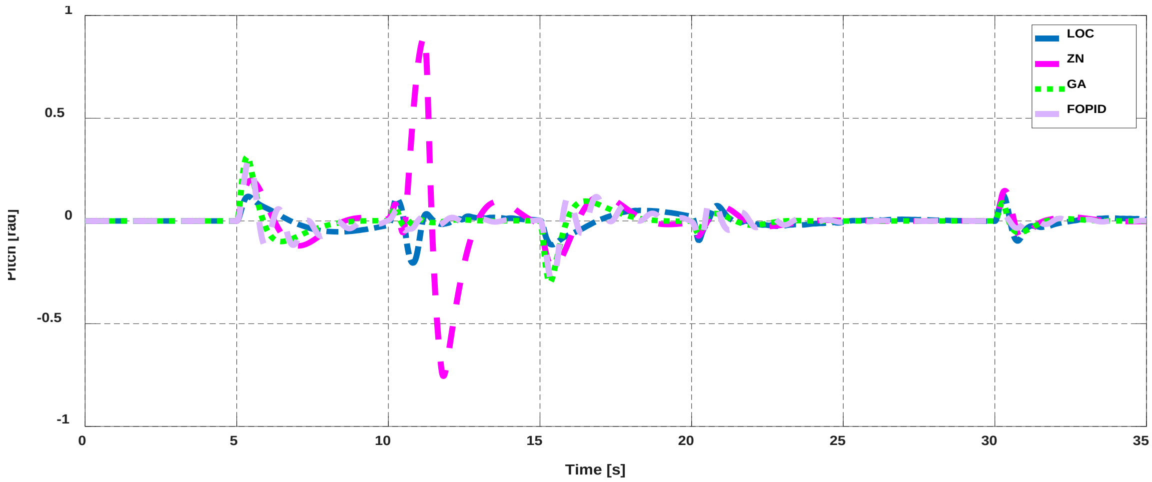

Figure 13. Pitch control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA under effect of wind disturbance.

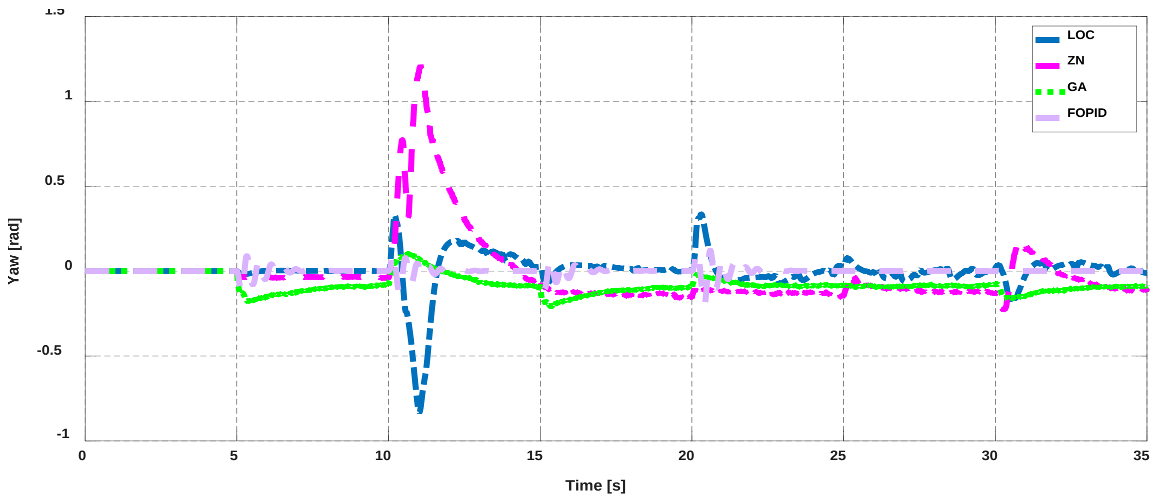

Figure 14. Yaw control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA under effect of wind disturbance.

The obtained results show the ability of the underlying controllers to stabilize and control the leader quadrotor under effect of sudden wind disturbances with superiority of BS-PID tuned by FOPID method.

Figures 12-15 display the trajectory tracking of single quadrotor controlled by BS-PID controller tuned by LOC, FOPID and BS-PD controllers tuned by ZN and GA under effect of white noise in in altitude and attitude orientations, respectively. The obtained results show the ability of the underlying controllers to stabilize and control the quadrotor under effect of white noise with superiority of BS-PID tuned by FOPID method.

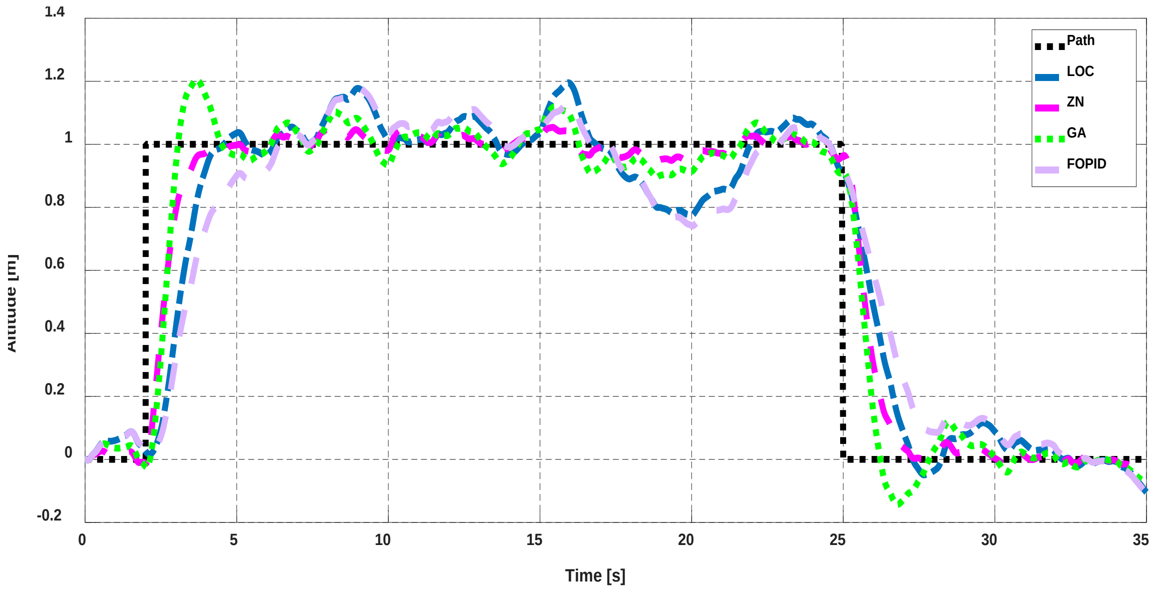

Figure 15. Trajectory tracking of BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA for a single quadrotor in ***Z***-orientation under effect of noise.

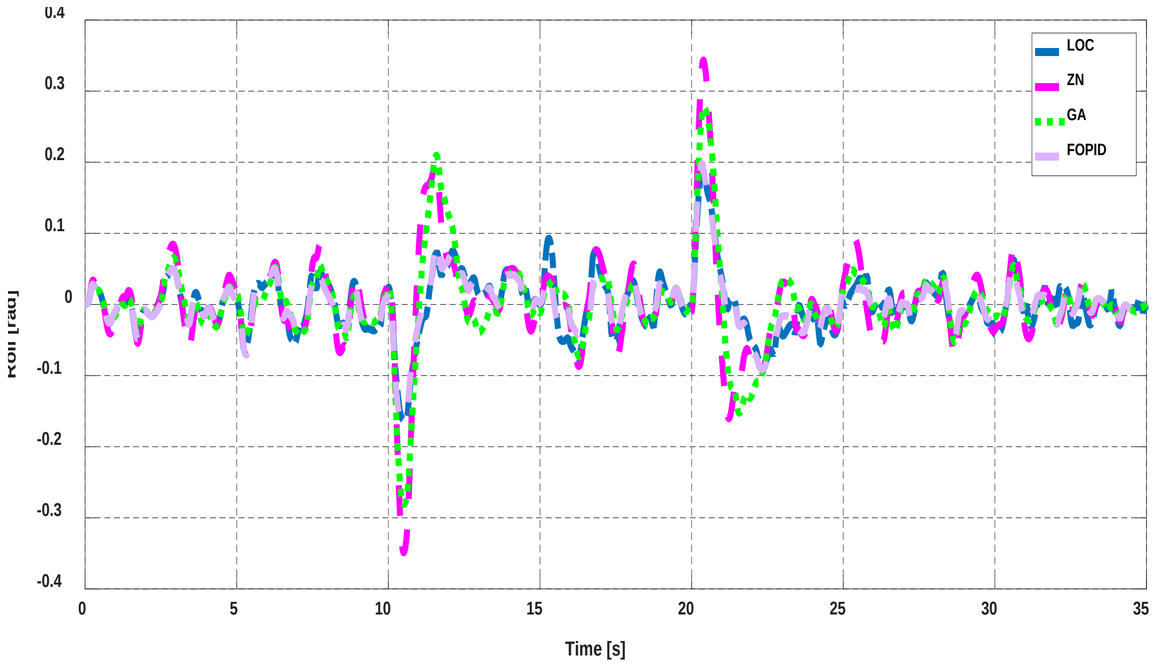

Figure 16. Roll control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA under effect of noise.

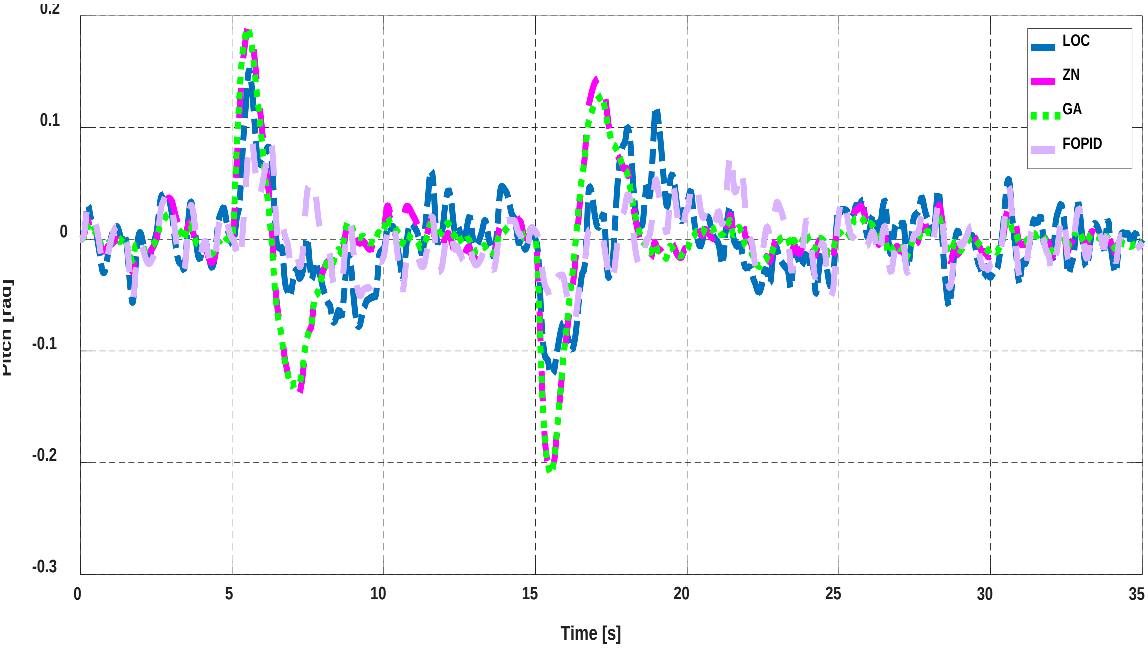

Figure 17. Pitch control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA under effect of noise.

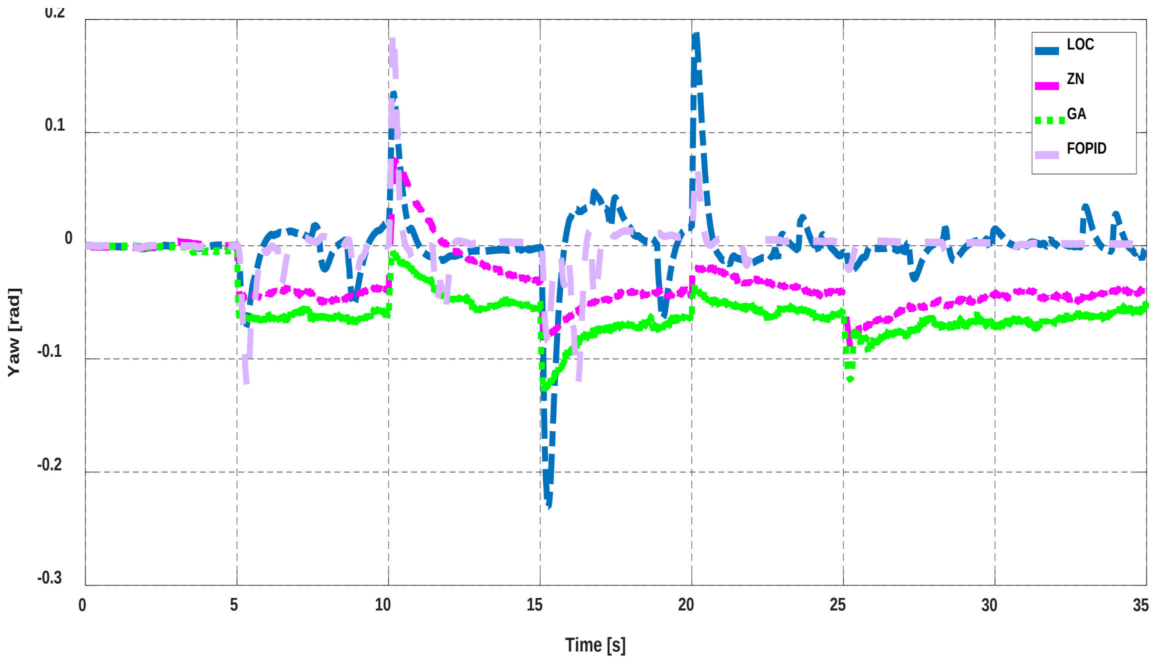

Figure 18. Yaw control for BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA under effect of noise.

Figures 16 shows the (X-Y) plane, the leader succeeded in tracking the desired path along the (X-Y) plane. Moreover, follower (1) and follower (2) respect the desired separating distances 40m and 30m along the X-axis and Y-axis, respectively. Follower (3) and follower (4) respect the desired separating distances 20m and 60m along the X-axis and Y-axis, respectively. Figure 17 displays the trajectory tracking of cooperative quadrotors controlled by BS-PID controller tuned by LOC, FOPID controller in XYZ orientations.

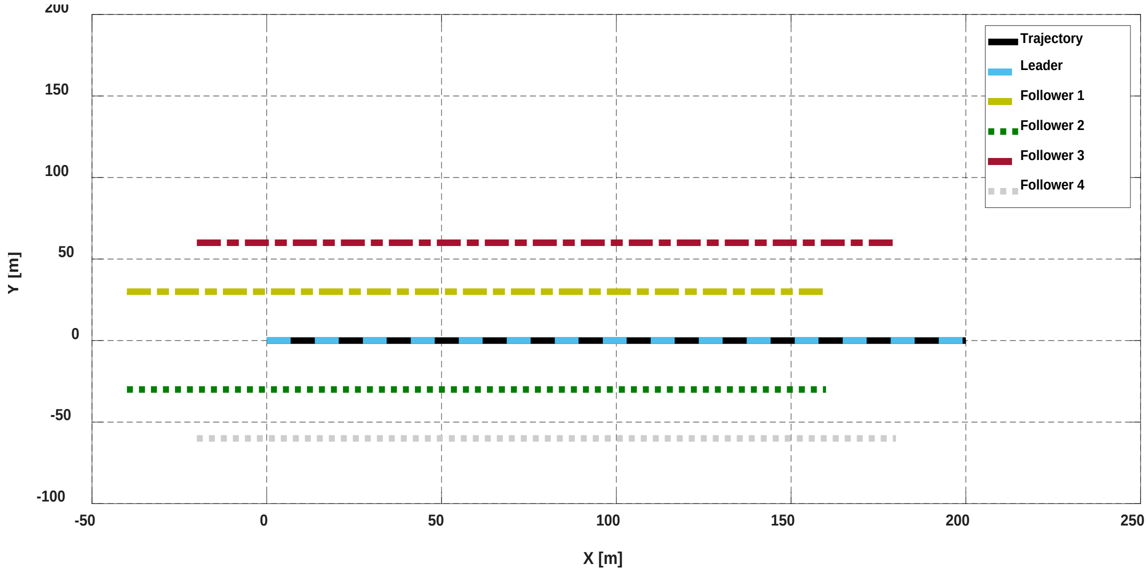

Figure 19. Trajectory tracking of BS-PID controller tuned by LOC, FOPID for cooperative quadrotors in XY-orientation.

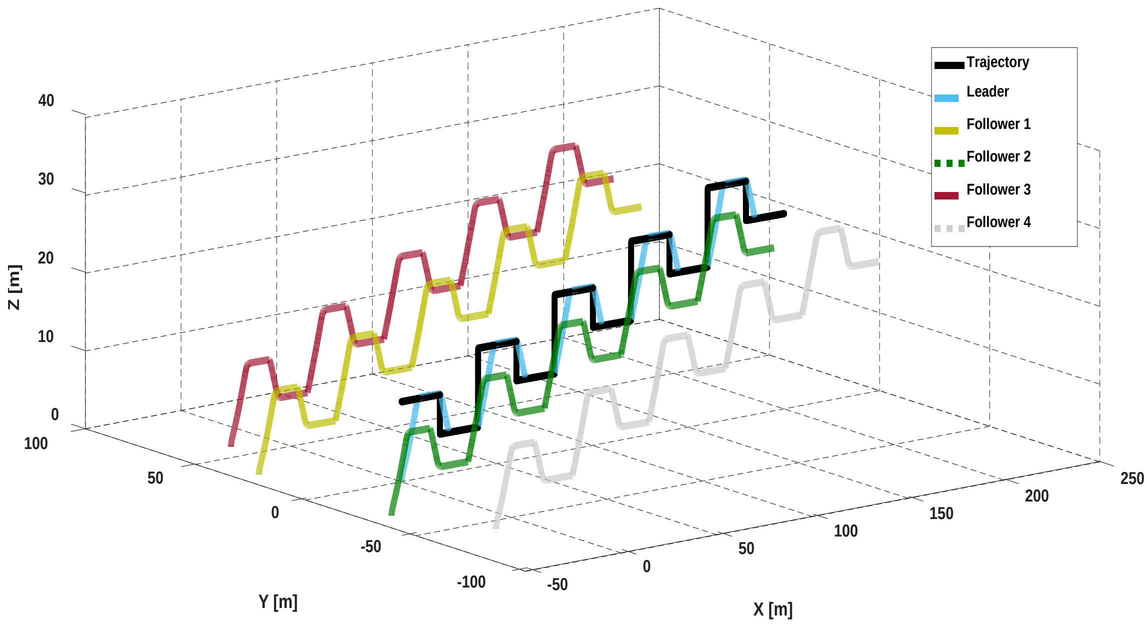

Figure 20. Trajectory tracking of BS-PID controller tuned by LOC, FOPID for cooperative quadrotors in XYZ-orientation.

4. Conclusion

In this paper, BS-PID controller tuned by LOC, FOPID, BS-PD controllers tuned by ZN and GA are conceived for dissolving formation configuration issues for cooperative quadrotors UAVs. A complete mathematical model for the underlying tunning approaches is presented. The simulation outcomes demonstrate a perfect stable flight attained by the proposed controller in the appearance and disappearance of applied disturbances and white noises. A comparison between the proposed controllers in different cases and orientations are studied. The outcomes demonstrate the superiority of BS-PID controller tuned by LOC, FOPID compared with BS-PID controller tuned by LOC, BS-PD controllers tuned by ZN and GA in the appearance and disappearance of applied disturbances and white noises.

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