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Formation configuration of unmanned cooperative quadrotors via PID tuning approaches

M Mahfouz [1], A Taiomour [2], M M Ashry [1] and G Elnashar [1]

[1]Department of Optoelectronics and Control, Military Technical College,
[2]Aircraft Armament Department, Military Technical College,

E-mail: m.mahfouz.trc@gmail.com,

Abstract. Formation configuration is one of the major intrinsic strategies used in cooperative Unmanned Air Vehicles field. In this paper, Backstepping-PID control technique for cooperative quadrotors unmanned aerial vehicles are developed to solve the formation problem. The proposed controller is divided into couple of parts working together. Backstepping 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 Fraction Order Approach, and Local Optimal Approach to refine the PID lower controller gains. The tunning of the PID gains through the proposed PID tuning approaches guarantee the stabilization of the attitude control for all the team members. Simulation results present the success of the proposed PID tuning approaches in solving the formation problem for cooperative unmanned quadrotors tracking a desired path. Moreover, the simulation results present the ability of the proposed approaches to handle disturbance rejection and noise attenuation while preserving the stability of the system.

1. Introduction

Deploying cooperative unmanned aerial vehicles (UAVs) is extremely relevant for wide areas of implementations in either military and civilian utilizations [1]. Currently, one of the most important UAVs is the vertical take-off and landing (VTOL) with four-rotors aircraft. It is well known as quadrotor. This kind of aircrafts 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) [3], which acts as fundamental foundation for design of control plan [4]. This makes control design is very challenging. currently, there are numerous methods to control the quadrotor, the literature [5], [6], [7], [8], and [9] 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 [10] and [11].
It is believed that multiple cooperative quadrotors are more stable and adaptable to fulfill the desired demands than single quadrotor [12]. 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 [13].
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.
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.
BS controller is used mostly as a higher controller [14]. BS controller is an effective control strategy for extremely nonlinear frameworks. The rapid convergence rate, the stability, the capability to manage nonlinear frameworks using recursive operation of Lyapunov function, the robustness regardless presence of uncertainties, and the simplicity are the benefits of BS controller [7]. The proposed BS-PID controller enhanced the overall performance and stability of the underlying cooperative quadrotors system. Whereas, Local Optimal Approach (LOA) is convenient for controlling non-linear systems with multivariable parameters as Single Input Single Output (SISO) systems [15]. Local Optimal PID (LOPID) is developed based on LOA theory and traditional PID theory. LOA is characterized with robust performance [16].
Multivariate control systems were given much attention because of the growing complexity of control systems operations [17]. Numerous researchers are broadly utilizing Fractional Order Approach (FOA) to accomplish better robust performance in several control systems. FOA approach has accomplished further remarkable outcomes on quadrotors particularly enhancing the stability of its frameworks.
The superiority of FOA 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 [18]. Fractional order PID (FOPID) is developed based on FOA theory and traditional PID theory. This controller expands the resolution of tuning parameters from the triple parameters of PID k_P, k_D, and k_I to five parameters by adding the FOC parameters λ and μ. Theses tunable parameters make the controller more precise, robust and flexible [19].
The main contribution of this paper is using LOPID and FOPID approaches with BS controller in the proposed cascaded controllers for first time in cooperative quadrotors. LOPID and FOPID are used to tune PID gains to stabilize attitude control for cooperative quadrotors.

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 [20]. BS approach is a preferred control technique over various approaches. The controller utilizes a recursive operation. It divides the controller mechanism into serial stages with respect of keeping the stability of every single stage progressively. 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} quadrotor (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 optimal control. PID are generally used because of design simplicity and reduced number of tunable parameters in the production controlled systems [21], and [22]. 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 [16]:

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

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 the dynamic. 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:

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

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

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

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:

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

The BS-PID tuned by LOPID and FOPID approaches 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.

The proposed controllers are divided into couple of parts working together. Backstepping controller is used to stabilize the position control as a higher controller. Simultaneously, PID tuned by LOPID and FOPID controllers receive the desired position to stabilize the attitude control as a lower controller to track the desired planning trajectories as depicted in Figures 1 and 2 respectively.

The BS-PID tuned by LOPID and FOPID approaches are studied in [23].

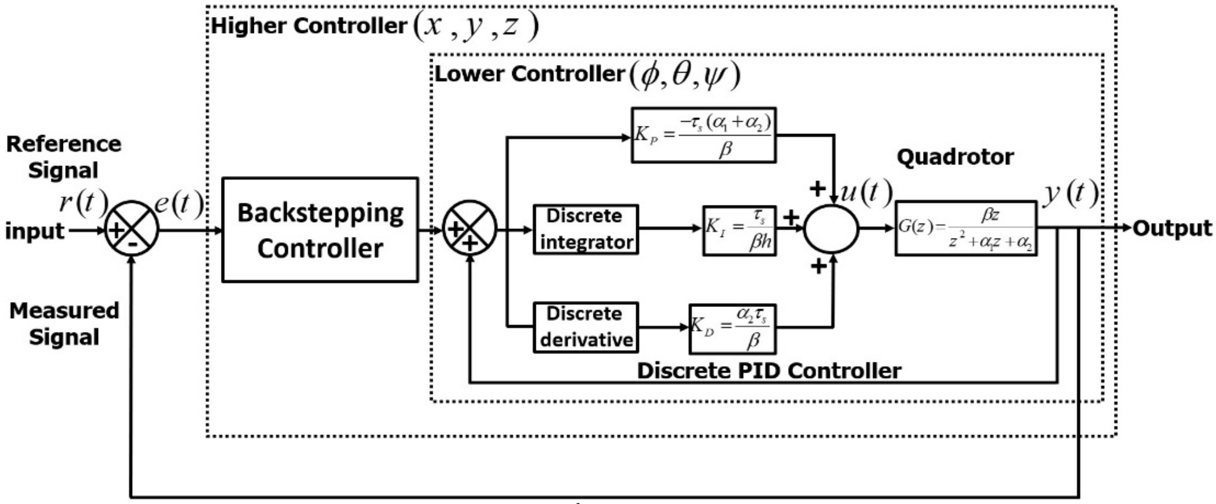

Figure 1. LOPID block diagram for 2nd order model of quadrotor framework.

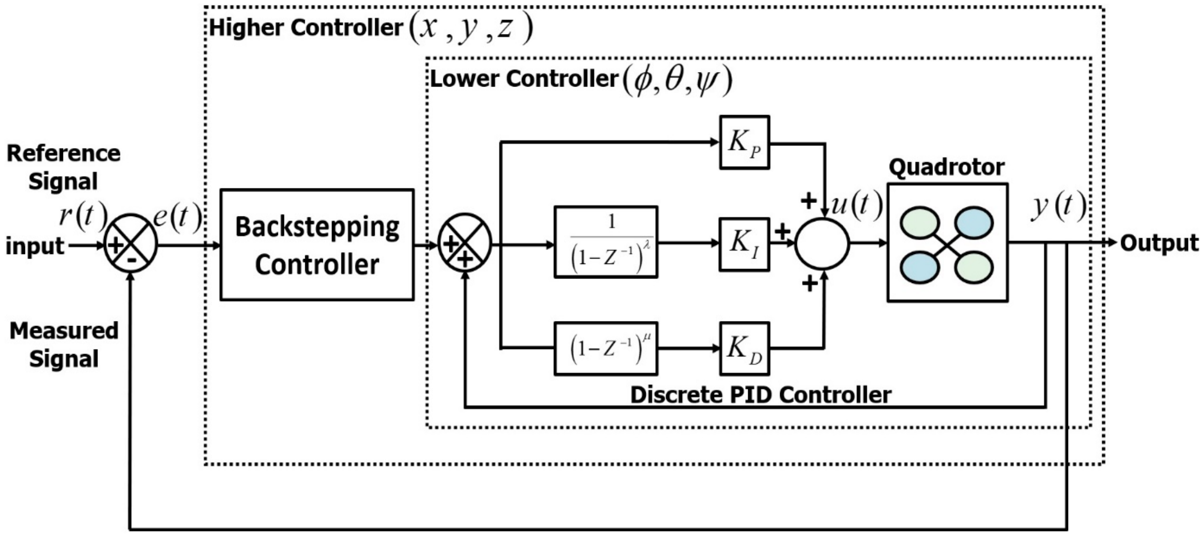

Figure 2. FOPID block diagram for 2nd order model of quadrotor framework.

3. Simulation results and comparative study

Several simulations trials on MATLAB Simulink are performed using the entire quadrotor model to modulate LOPID and FOPID control coefficients.

The controller's function of LOPID and FOPID 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 approach to keep the planned formation configuration.

The comparative criterion between the offered controller includes designed trajectory tracking, wind disturbance rejection, and noise cancellation.

3.1. Local Optimal PID Approach

The underlying quadrotors are examined in path tracking in an ideal case of free flight and in the absence of applied noise and wind disturbance.

The team is composed from a leader and four followers tracking a desired path along the three axes. Figures 3-8 display the trajectory tracking of cooperative quadrotors controlled by BS-PID controller tuned by LOPID controller in X, Y, and Z orientations with their velocities, respectively.

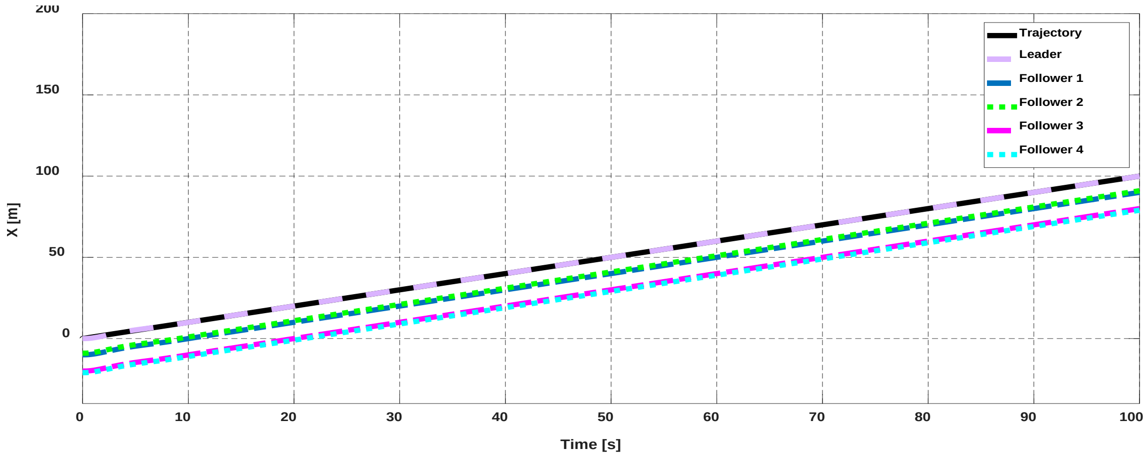

Figure 3. Trajectory tracking of BS-PID controller tuned by LOPID for cooperative quadrotors in ***X***-orientation.

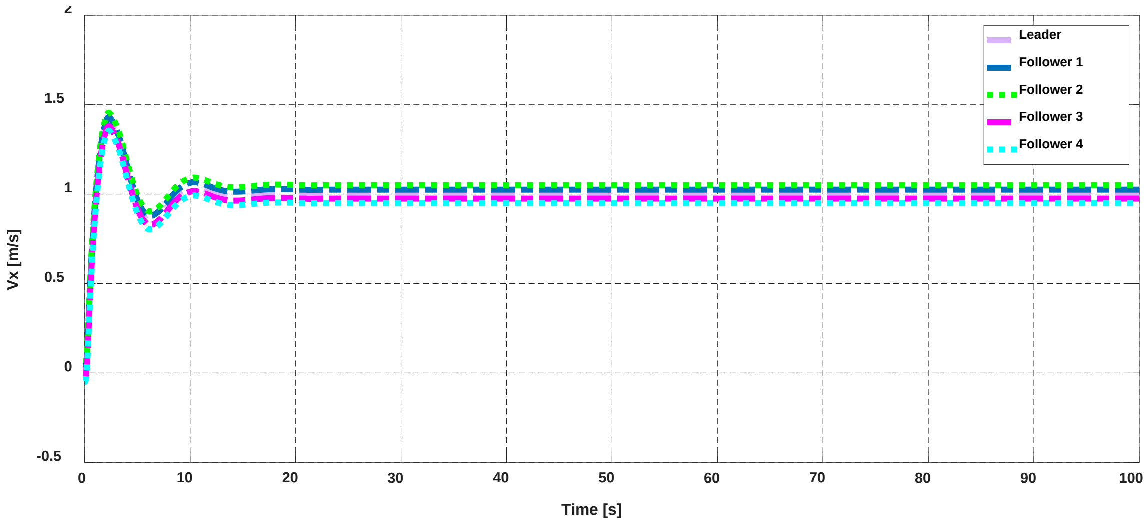

Figure 4. Velocity of cooperative quadrotors in ***X***-orientation.

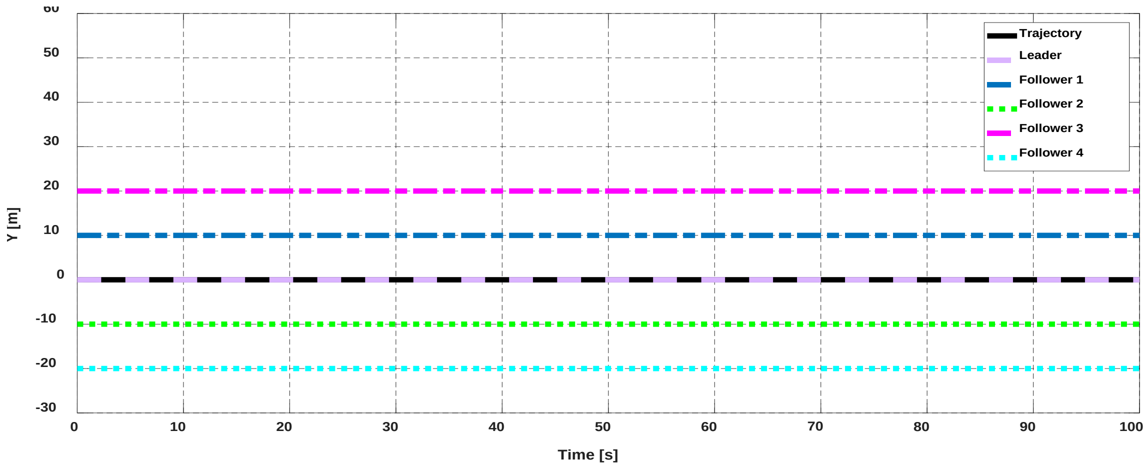

Figure 5. Trajectory tracking of BS-PID controller tuned by LOPID for cooperative quadrotors in ***Y***-orientation.

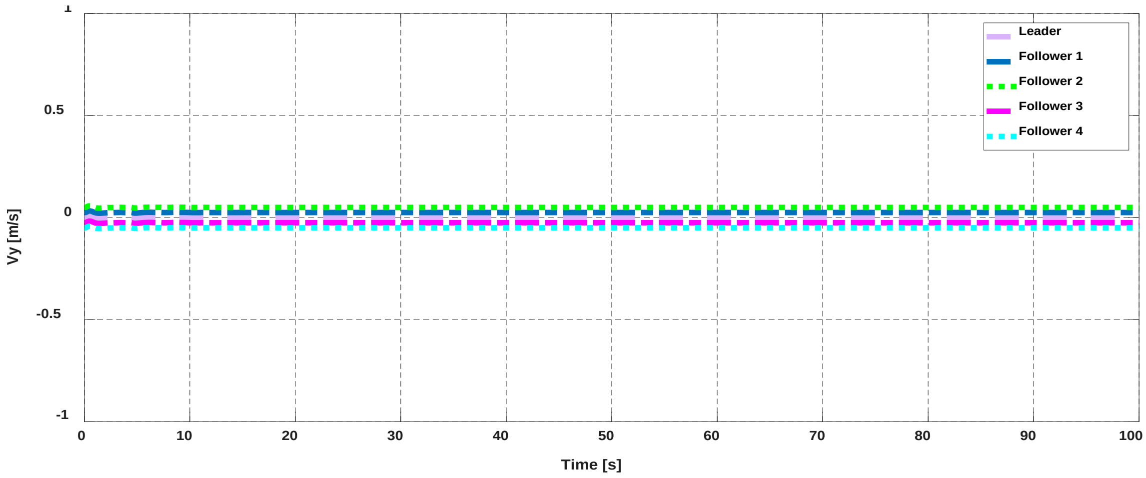

Figure 6. Velocity of cooperative quadrotors in ***Y***-orientation.

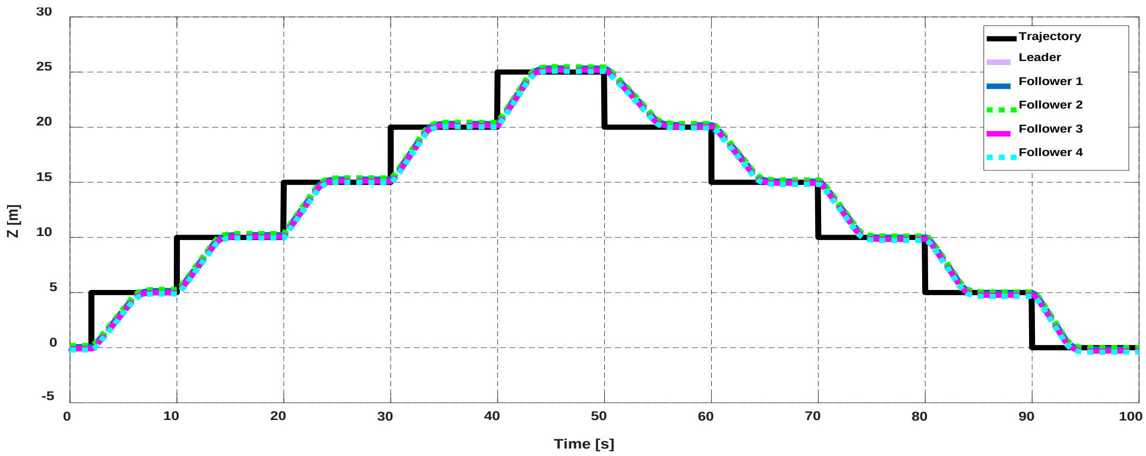

Figure 7. Trajectory tracking of BS-PID controller tuned by LOPID for cooperative quadrotors in ***Z***-orientation.

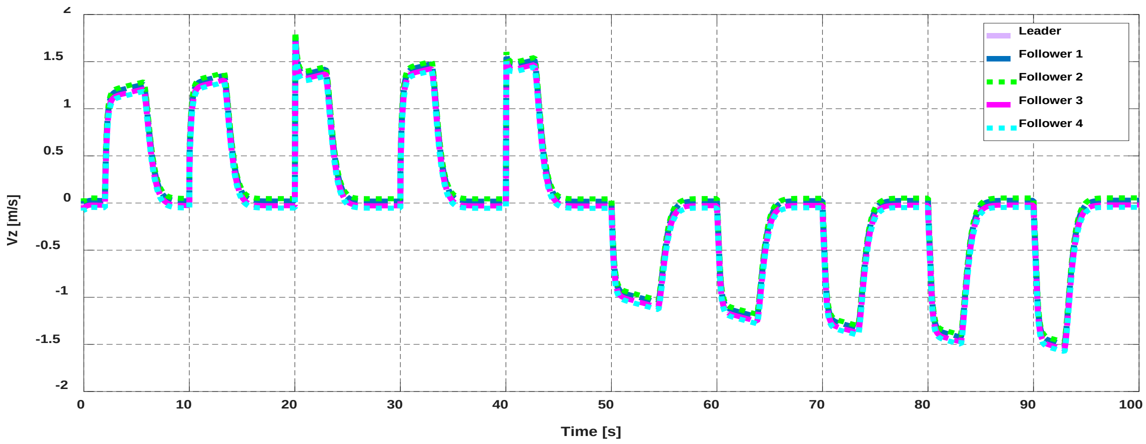

Figure 8. Velocity of cooperative quadrotors in ***Z***-orientation.

Figures 3-8 show successful of the trajectory tracking for a team of cooperative quadrotors controlled by BS-PID controller tuned by LOPID, and their velocities respect the designed constraints 2 m/sec. Figure 9 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 10m along the

X-axis and Y-axis. Follower (3) and follower (4) respect the desired separating distances 20m along the X-axis and Y-axis. Figure 10 displays the trajectory tracking of cooperative quadrotors controlled by BS-PID controller tuned by LOPID in XYZ orientations.

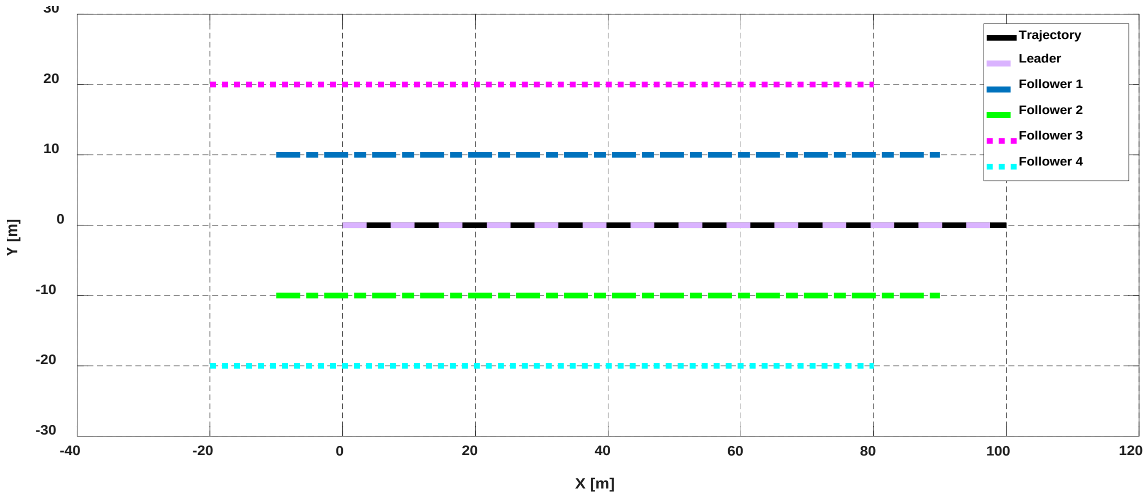

Figure 9. Trajectory tracking of BS-PID controller tuned by LOPID for cooperative quadrotors in ***XY***-orientation.

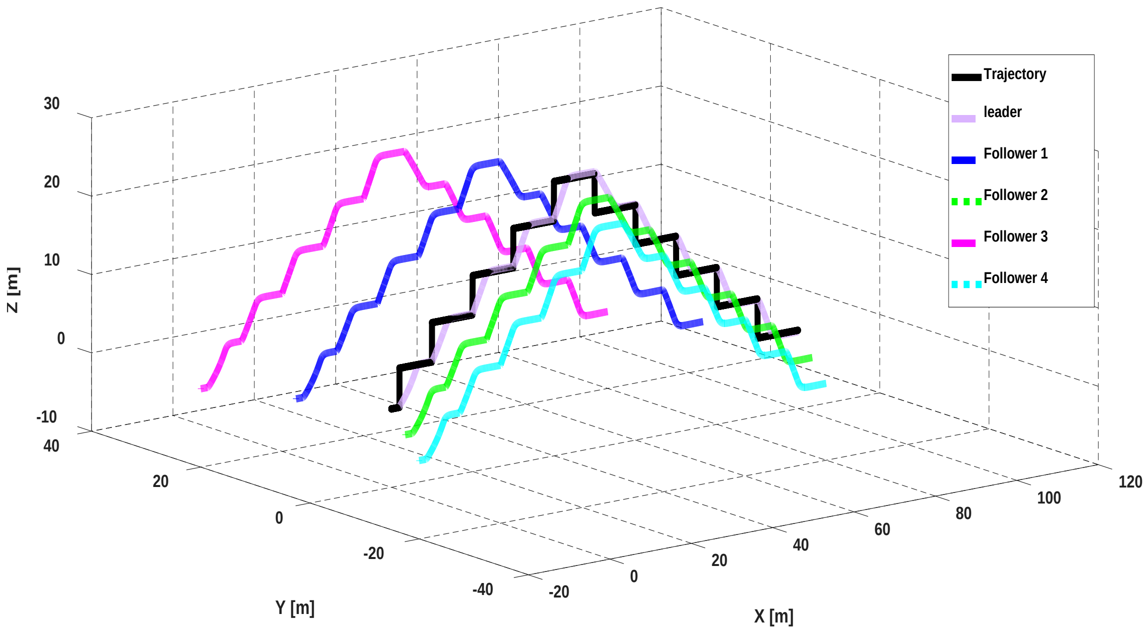

Figure 10. Trajectory tracking of BS-PID controller tuned by LOPID for cooperative quadrotors in ***XYZ***-orientation.

Figures 3-10 show successful of the trajectory tracking for a team of cooperative quadrotors controlled by BS-PID controller tuned by LOPID, and their velocities respect the designed constraints 2 m/sec. Figures 11-13 display the roll, pitch, and yaw channels of cooperative quadrotors controlled by BS-PID controller tuned by LOPID controller, respectively. All the quadrotors respect the desired angles during the free flight.

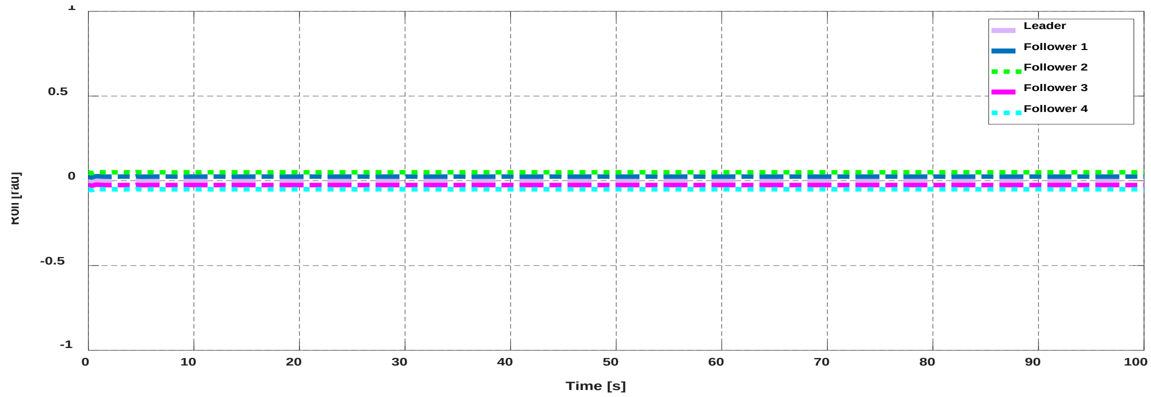

Figure 11. Roll control of BS-PID controller tuned by LOPID for cooperative quadrotors.

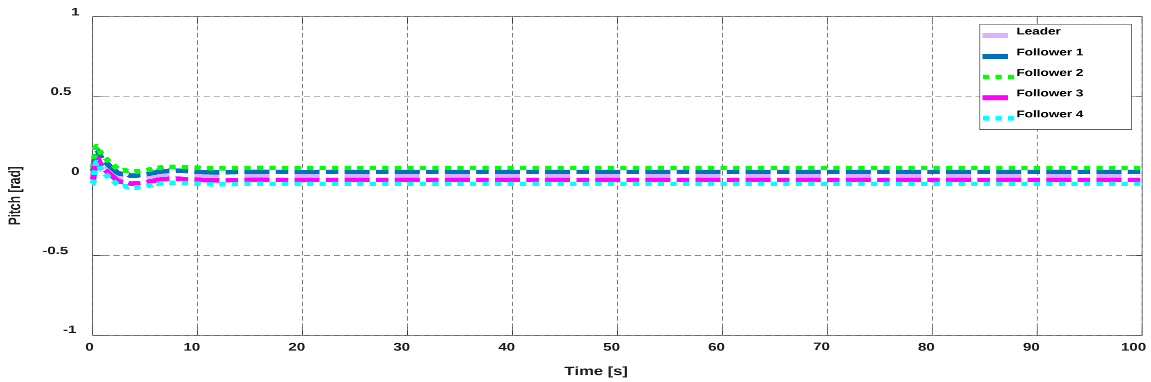

Figure 12. Pitch control of BS-PID controller tuned by LOPID for cooperative quadrotors.

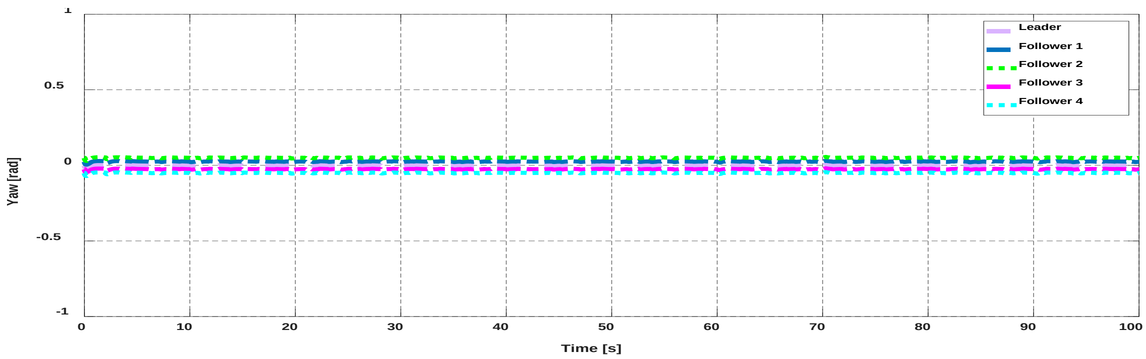

Figure 13. Yaw control of BS-PID controller tuned by LOPID for cooperative quadrotors.

Figures 11-13 show successful of the trajectory tracking of cooperative quadrotors controlled by BS-PID controller tuned by LOPID.

3.2. Fractional Order PID Approach

The underlying quadrotors are examined in path tracking in an ideal case of free flight and in the absence of applied noise and wind disturbance.

The team is composed from a leader and four followers tracking a desired path along the three axes. Figures 14-19 display the trajectory tracking of cooperative quadrotors controlled by BS-PID controller tuned by FOPID controller in $X, Y,$ and Z orientations with their velocities, respectively.

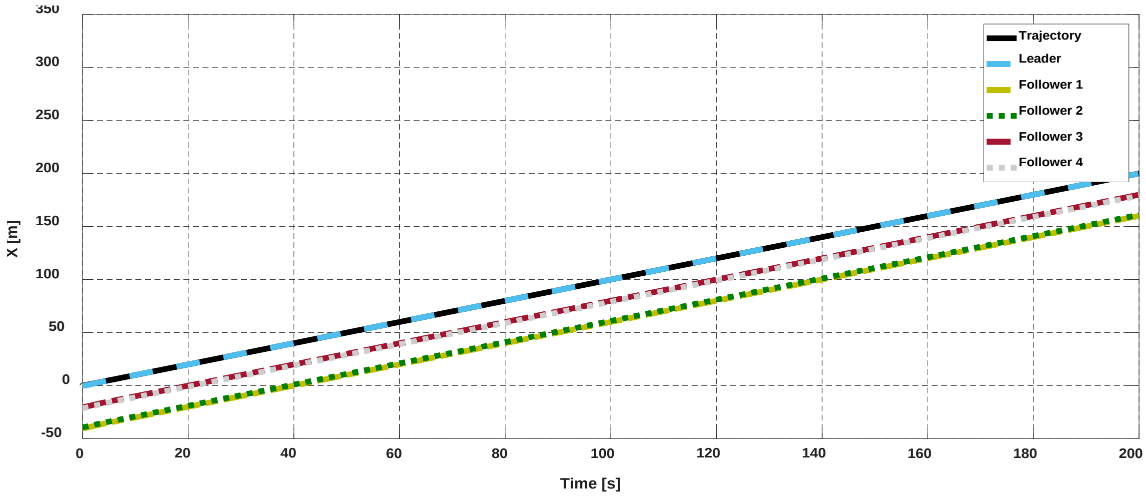

Figure 14. Trajectory tracking of BS-PID controller tuned by FOPID for cooperative quadrotors in ***X***-orientation.

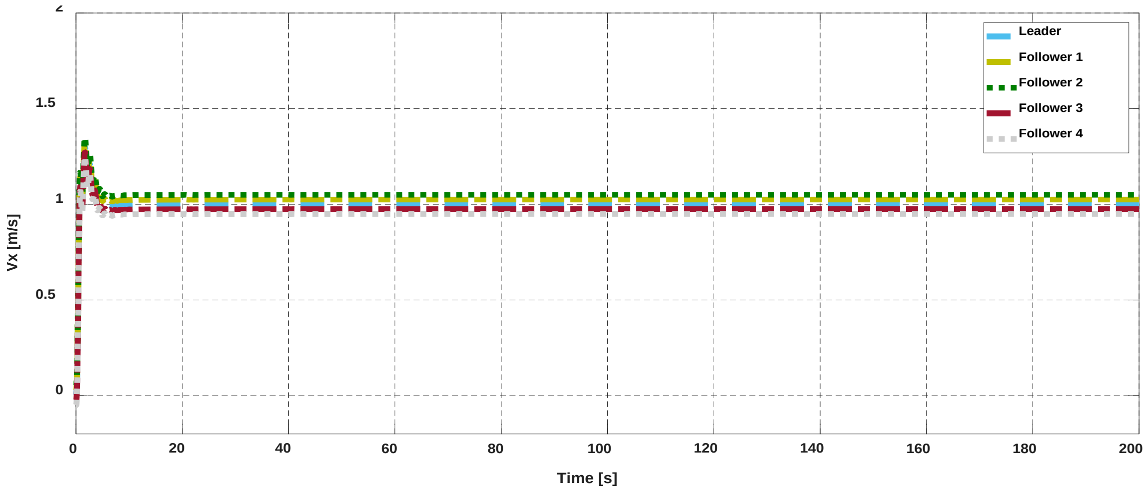

Figure 15. Velocity of cooperative quadrotors in ***X***-orientation.

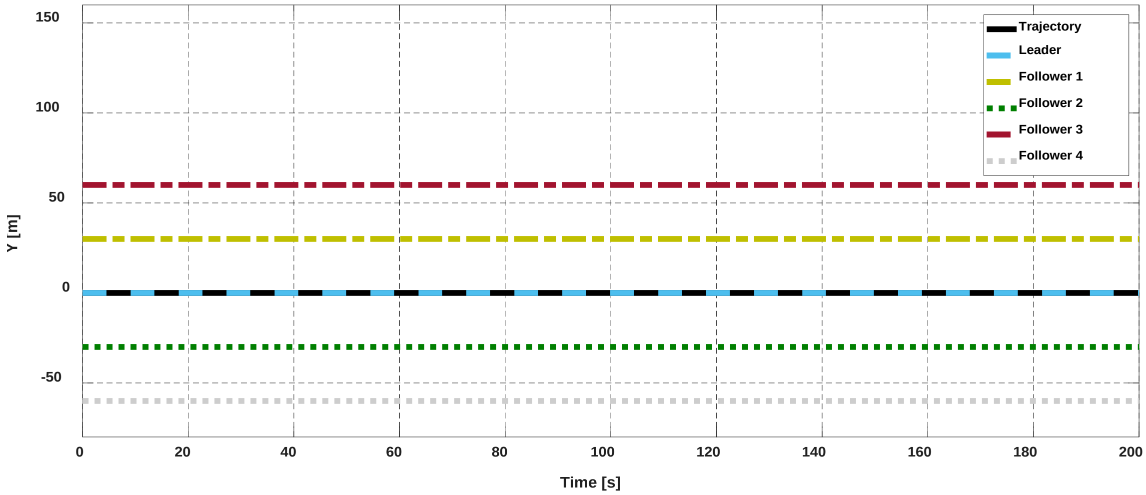

Figure 16. Trajectory tracking of BS-PID controller tuned by FOPID for cooperative quadrotors in ***Y***-orientation.

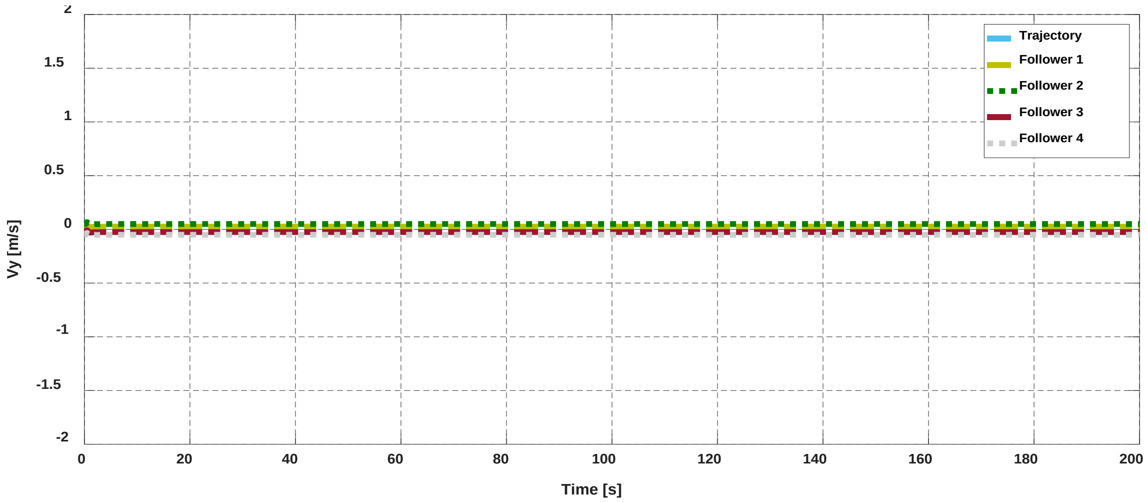

Figure 17. Velocity of cooperative quadrotors in ***Y***-orientation.

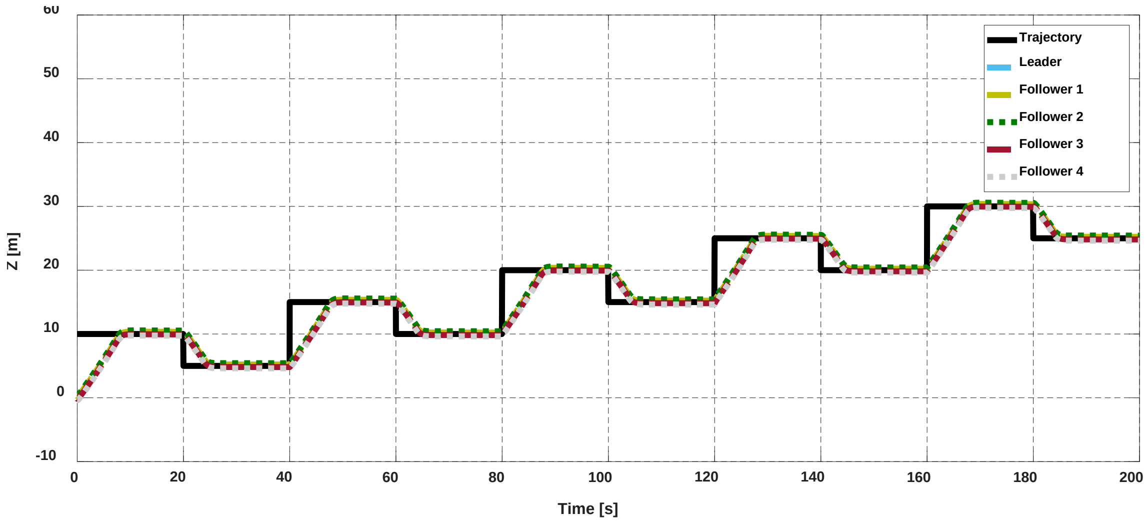

Figure 18. Trajectory tracking of BS-PID controller tuned by FOPID for cooperative quadrotors in ***Z***-orientation.

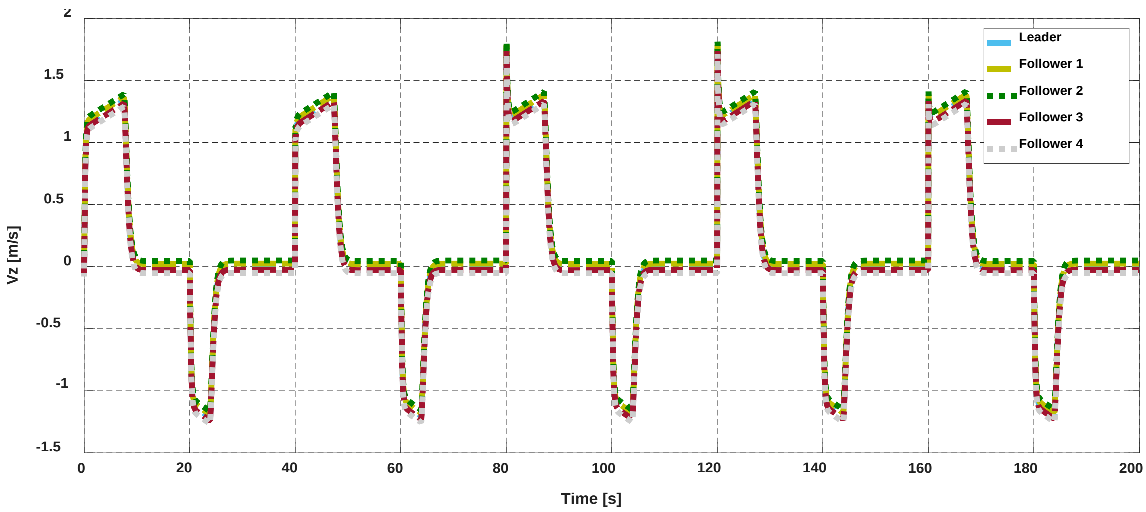

Figure 19. Velocity of cooperative quadrotors in ***Z***-orientation.

Figures 14-19 show successful of the trajectory tracking for a team of cooperative quadrotors controlled by BS-PID controller tuned by FOPID, and their velocities respect the designed constraints 2 m/sec.

Figures 20 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 21 displays the trajectory tracking of cooperative quadrotors controlled by BS-PID controller tuned by FOPID in XYZ orientations.

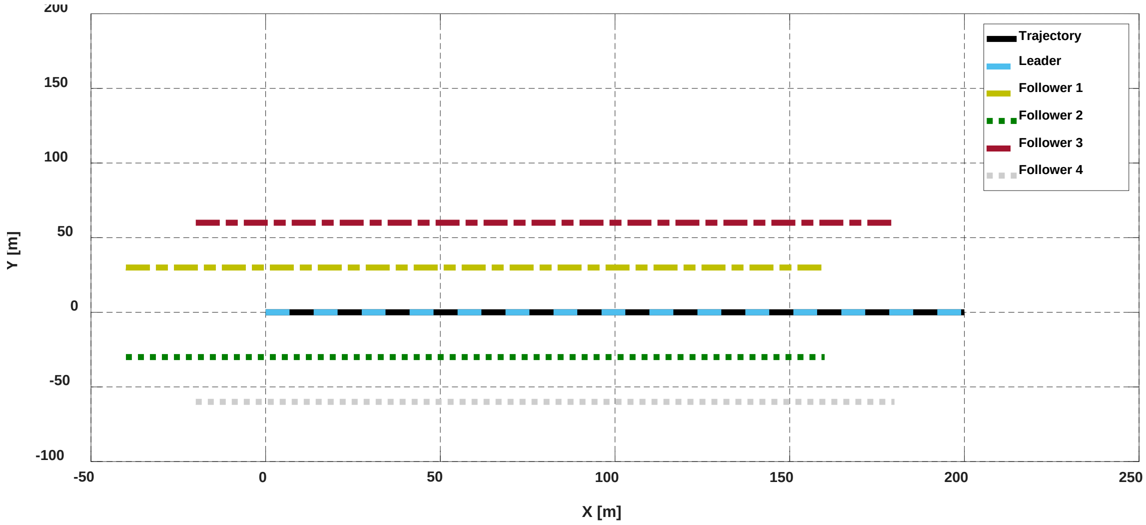

Figure 20. Trajectory tracking of BS-PID controller tuned by FOPID for cooperative quadrotors in $\boldsymbol{XY}$-orientation.

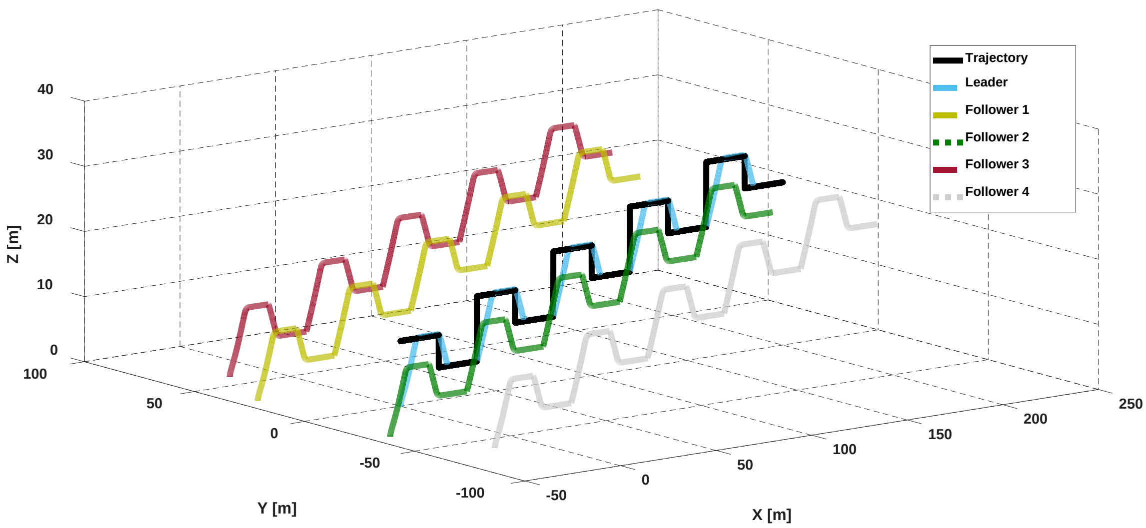

Figure 21. Trajectory tracking of BS-PID controller tuned by FOPID for cooperative quadrotors in $\boldsymbol{XYZ}$-orientation.

Figures 22-24 display the roll, pitch, and yaw channels of cooperative quadrotors controlled by BS-PID controller tuned by FOPID controller, respectively. All the quadrotors respect the desired angles during the free flight.

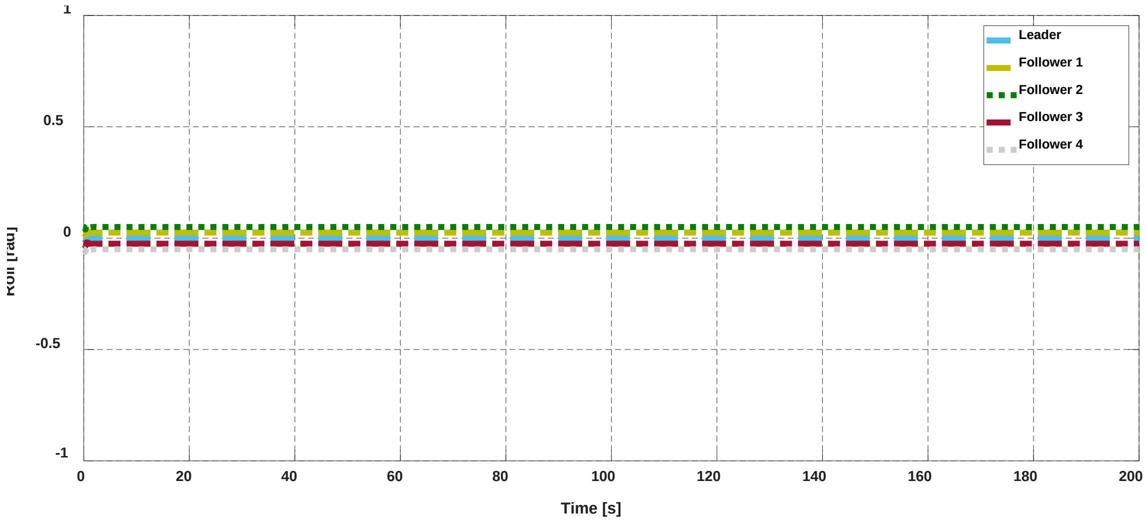

Figure 22. Roll control of BS-PID controller tuned by FOPID for cooperative quadrotors.

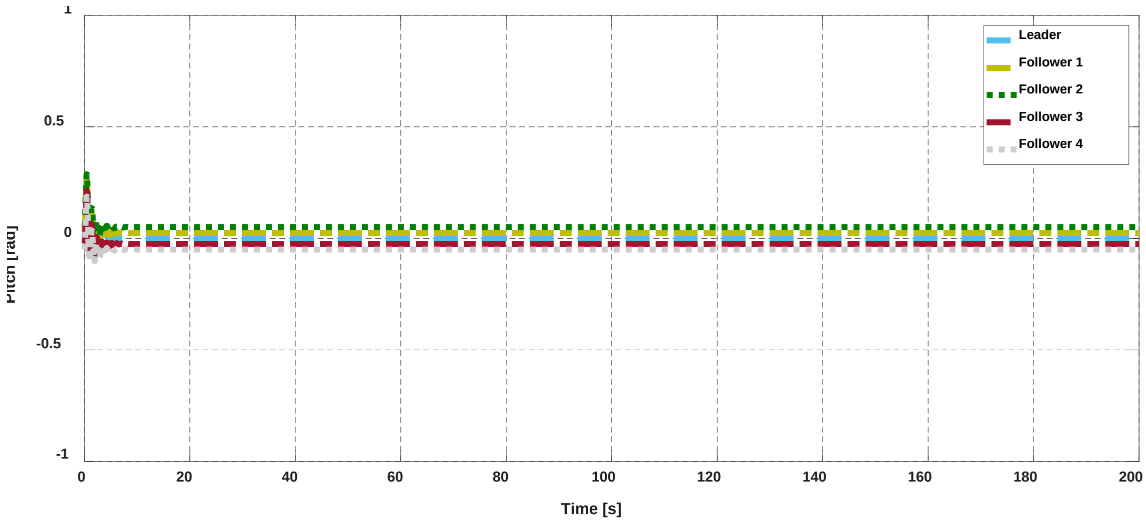

Figure 23. Pitch control of BS-PID controller tuned by FOPID for cooperative quadrotors.

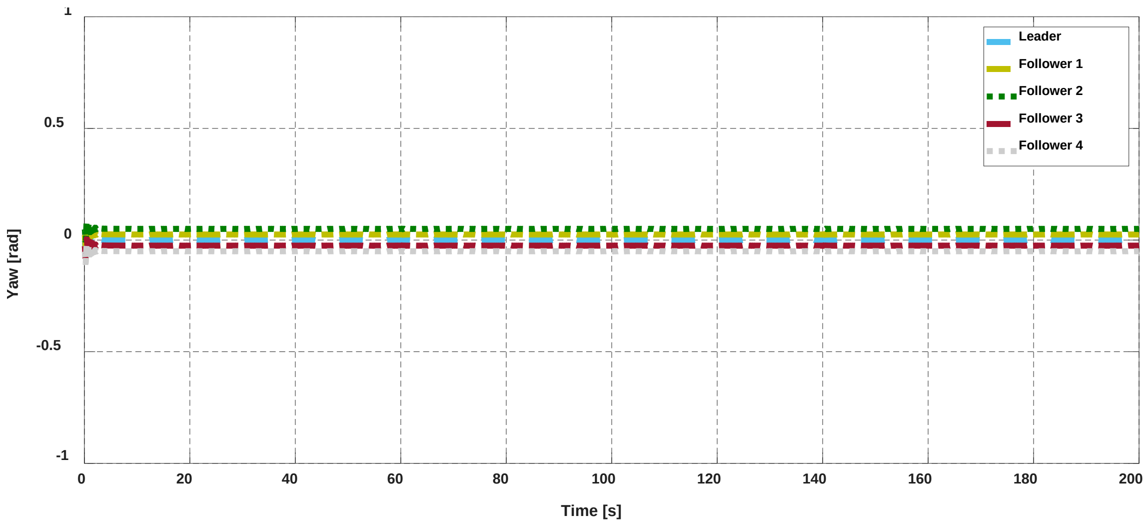

Figure 24. Yaw control of BS-PID controller tuned by FOPID for cooperative quadrotors.

3.3. Wind disturbance rejection and noise attenuation scenario:

Stability and robustness evaluation of BS-PID controller tuned by LOPID and FOPID controller are realized. The proposed controllers are checked on the leader of the cooperative quadrotors in different trajectories. The proposed controllers are checked and compared together in the presence of wind disturbance and noise to show their robustness.

Figures 25-28 display the trajectory tracking of the leader of the cooperative quadrotors controlled by BS-PID controller under the effect of wind disturbance in altitude and attitude orientations, respectively. The wind disturbances are represented as a sudden pulse at a periodic time of 10 sec in different direction to show the ability of the introduced approach to reject it. The obtained results show the ability of the underlying controllers to stabilize and control the leader quadrotor under effect of wind disturbances.

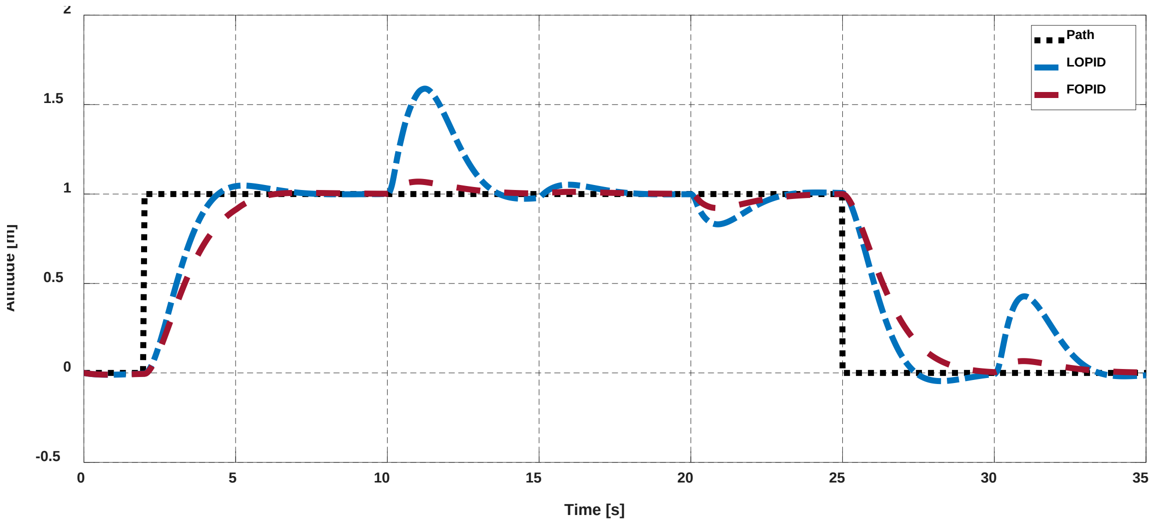

Figure 25. Trajectory tracking of BS-PID controller tuned by LOPID and FOPID for the leader of the cooperative quadrotors in Z-orientation under effect of wind disturbance.

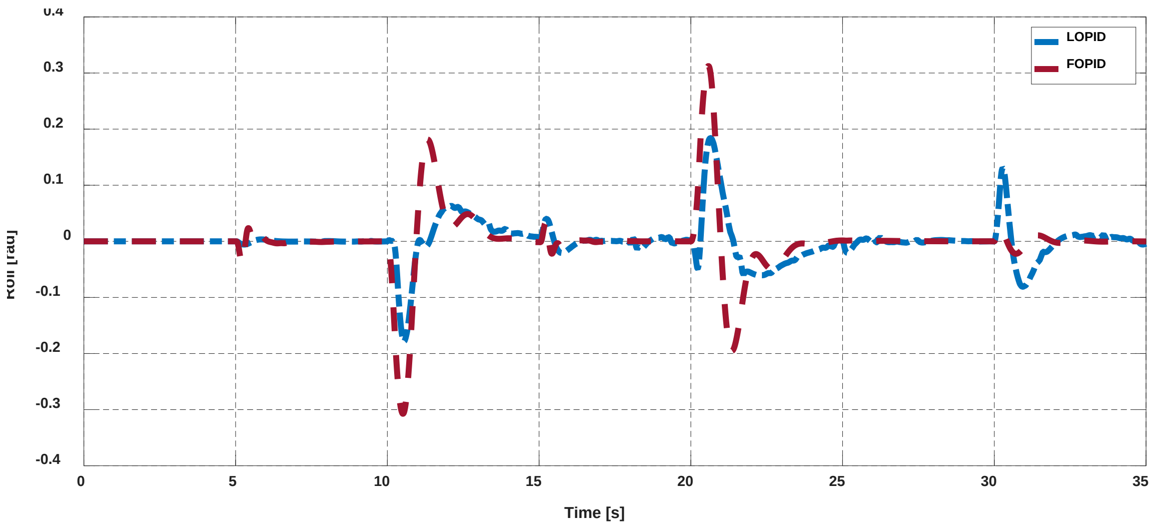

Figure 26. Roll control for BS-PID controller tuned by LOPID and FOPID under effect of wind disturbance.

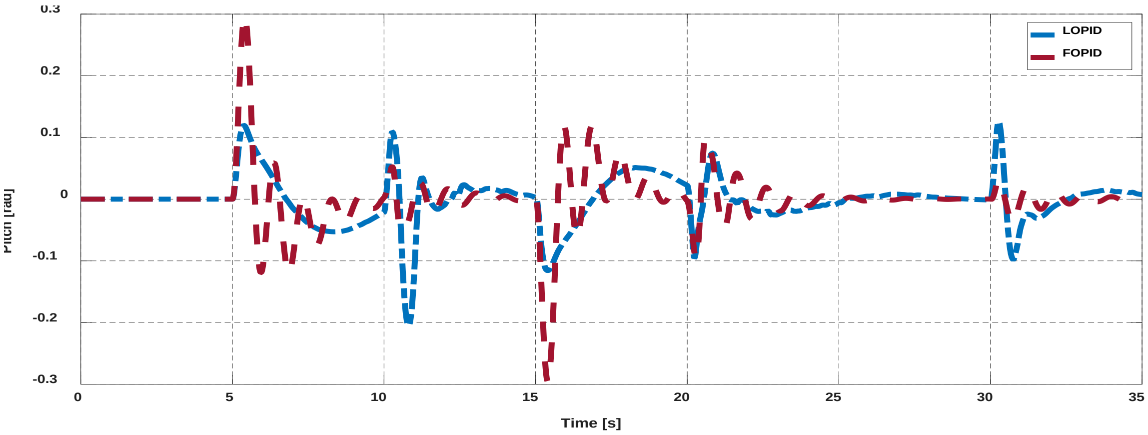

Figure 27. Pitch control for BS-PID controller tuned by LOPID and FOPID under effect of wind disturbance.

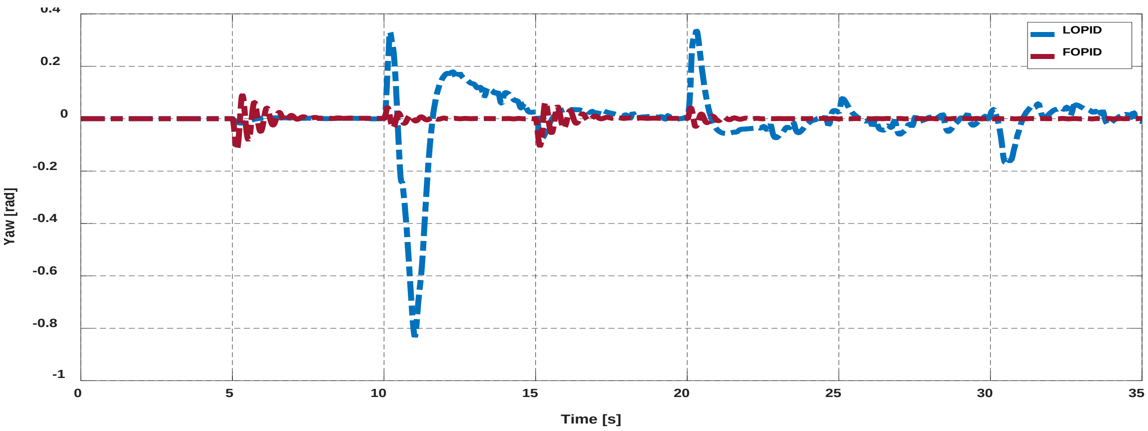

Figure 28. Yaw control for BS-PID controller tuned by LOPID and FOPID under effect of wind disturbance.

Figures 29-32 display the trajectory tracking of the leader of the cooperative quadrotors controlled by BS-PID controller under the effect of sudden noise in altitude and attitude orientations, respectively. The obtained results show the ability of the underlying controllers to stabilize and control the leader quadrotor under effect of white noise.

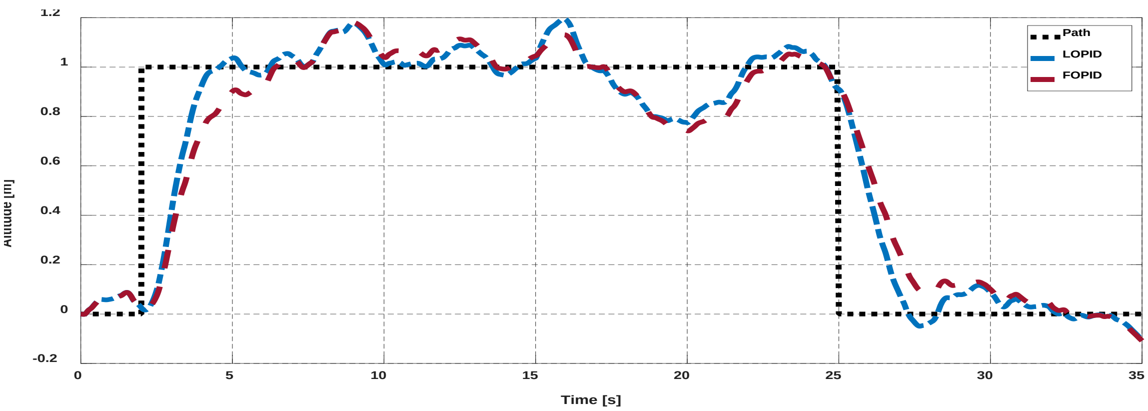

Figure 29. Trajectory tracking of BS-PID controller tuned by LOPID and FOPID for the leader of the cooperative quadrotors in $\boldsymbol{Z}$-orientation under effect of noise.

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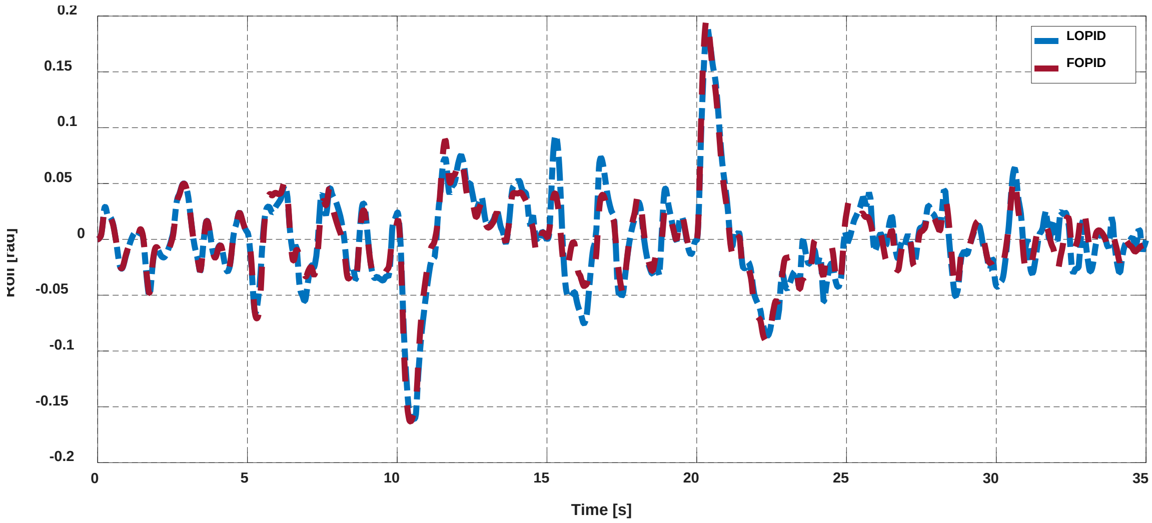

Figure 30. Roll control for BS-PID controller tuned by LOPID and FOPID under effect of noise.

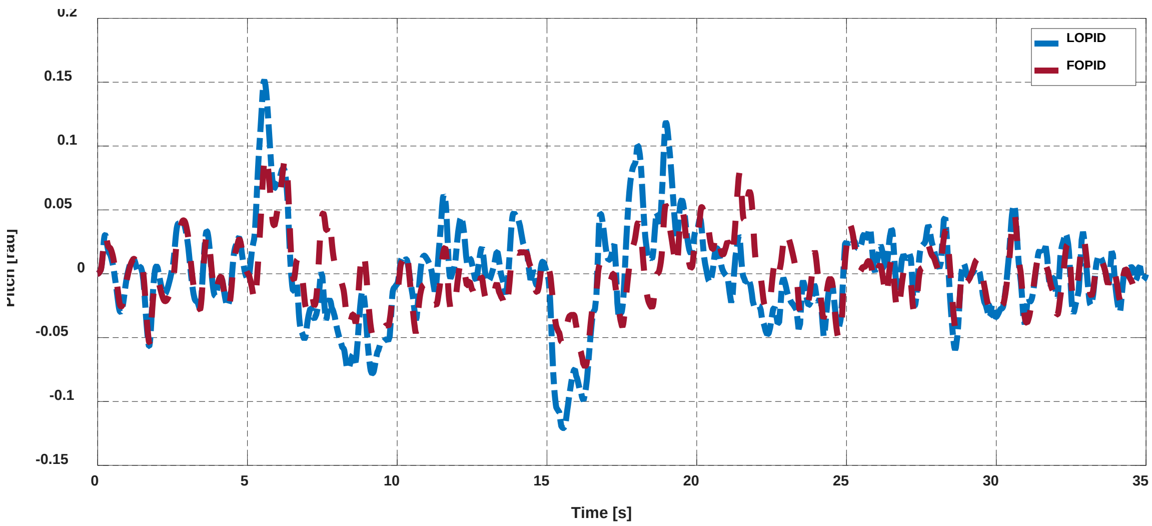

Figure 31. Pitch control for BS-PID controller tuned by LOPID and FOPID under effect of noise.

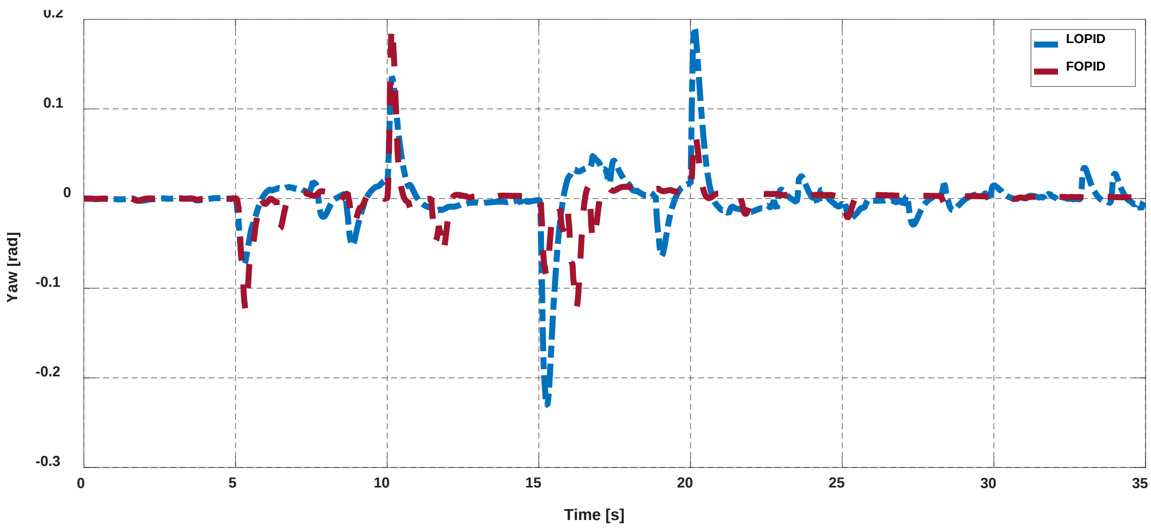

Figure 32. Yaw control for BS-PID controller tuned by LOPID and FOPID under effect of noise.

4. Conclusion

In this paper, BS-PID controller tuned by LOPID and FOPID is conceived for dissolving formation configuration issue for cooperative quadrotors UAVs. Couple of scenarios were presented to show the ability of the introduced approaches in solving the formation problem. The simulation outcomes demonstrate a perfect stable flight attained by the proposed controllers in the appearance and disappearance of applied disturbances and white noises. The simulation results show the superiority of FOPID over LOPID. Future work, the proposed approaches will be applied to solve the formation problem for cooperative unmanned vehicles in an obstacle loaded environment.

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