ADAPTIVE TRAJECTORY TRACKING CONTROL OF A QUADROTOR BASED ON ITERATIVE LEARNING ALGORITHM

Mohammad Mehdi Farzaneh[a*] iD **, Alireza Tavakolpour-Saleh[a]** iD

[a]Department of Mechanical Engineering, Shiraz University of Technology, Iran
m.farzaneh@sutech.ac.ir ([*] corresponding author), tavakolpour@sutech.ac.ir

Abstract

This paper presents a new adaptive and optimal algorithm for the trajectory tracking control of a quadrotor using iterative learning algorithm (ILA) and enumerative learning method. Ordinarily the ILA, as an adaptive method, can perform well with PID control to improve the controller's performance for a nonlinear system. Quadrotors are considered as nonlinear and unstable systems in which the use of an adaptive and optimal controller can increase its stability and decrease error level. In this method, a PID controller is proposed for the inner and outer control loops of a quadrotor and the ILA is used to adapt PID control gains. Subsequently, an enumerative learning algorithm is used to optimize the learning rates of the ILA. For this purpose, at first, the dynamic model of the quadrotor is acquired. After that, the structure of the control system and the inner and outer control loops are defined. In the end, the simulation results for the trajectory tracking control are demonstrated. Through simulation, it is concluded that as time increases, the performance of the suggested control method in trajectory tracking control becomes better and better and error signals convergence to zero.

Keywords: Quadrotor, trajectory tracking control, PID control, iterative learning algorithm

1. Introduction

Quadrotor is the four-propeller type of unmanned aerial vehicles and has a wide range of utilities in civilian and military applications. Basically, the quadrotor differs from the common helicopter, which uses rotors with dynamically varying pitch blades. Quadrotor's smaller blades are a useful feature since they contain less kinetic energy thus reducing their ability to cause damage. Owing to the simple and low-cost build and high maneuverability, quadrotors are the most common and popular flying robots in the world. The quadrotor has four inputs and six coupled outputs. Moreover, it is considered as an under-actuated and highly nonlinear system. So, design and implement a control system for quadrotor had been a challenge in recent years.

PID control algorithm is a common method in control and robotics. A cascade control based on generalized predictive controller and PID controller was applied to regulate the position of a quadrotor [1]. A recursive algorithm for a PID controller was designed to simplify the calculation stages concerning the tracking errors [2]. A PID controller with an extended Kalman filter was studied to filter out the sensors and system noises [3]. Fuzzy control logic was developed to adjust classic PD and PID control for quadrotor stability control [4]. To deal with uncertainties, a linear quadratic regulator controller was applied for better stabilization and improving the flight quality of quadrotor under noisy sensor measurements [5]. A sliding mode controller was obtained based on the back-stepping method for stabilization of a quadrotor [6]. Model reference adaptive and fixed gain linear quadratic regulator controllers were implemented for a quadrotor with parametric uncertainties [7]. An intelligent control algorithm based on particle swarm optimization was used to increase the performance of controllers in the presence of disturbances [8, 9].

There are several algorithms for trajectory tracking control of the quadrotor. A Fuzzy control was applied to set the PID-ILC parameters to restrain the influence of uncertain factors and improve the control precision [10]. A combination of Fuzzy control and PID control was applied to tune the control parameters of a model reference adaptive control for the altitude and attitude control of a tricopter [11]. A combination of the integral back-stepping control with the sliding mode control was studied for stabilization of a quadrotor attitude and to accomplish the task of trajectory tracking control [12, 13]. The effectiveness of a PID control and a back-stepping control for trajectory tracking control was evaluated by simulation results [14]. An adaptive controller was designed for an autonomous quadrotor using nonlinear dynamic inversion and neuro-adaptive methods [15]. A geometric sliding mode controller was designed to improve the robustness and accelerate the convergence rate of trajectory tracking control [16].

In this paper, an adaptive and optimal control algorithm is designed for the trajectory tracking control of quadrotor. Typically, the ILA is considered as an adaptive algorithm through which the performance of a control system becomes better and better as time increases. By this mean, a PID controller adapted by the P-type ILA is used for attitude control and a PID controller adapted by the PID-type ILA is used for altitude and position control. Meanwhile, an enumerative learning algorithm is designed to select the optimum learning rates for the ILA. Therefore, the layout of this paper is as follows. In Section 2, the complete 6-DOF dynamic model of the quadrotor is discussed. The structures of the control system and the inner and outer control loops are described in Section 3. Section 4 illustrates the performance of the baseline control method in trajectory tracking control through simulation. Finally, in Section 5 this document is terminated with the conclusion and the inspiration that can be derived from this work.

2. Quadrotor modeling

The complete 6-DOF dynamic model of the quadrotor is presented in this section. For this mean, the system of coordinates to use should be defined first. There are two reference frames: an earth frame indicated by the "*e*" index and a body-fixed frame indicated by the "*b*" index. The earth frame is located at the operator's position and the body-fixed frame origin is coinciding with the center of the gravity. Figure 1 shows a conceptual scheme of the quadrotor, reference frames, and Euler angles.
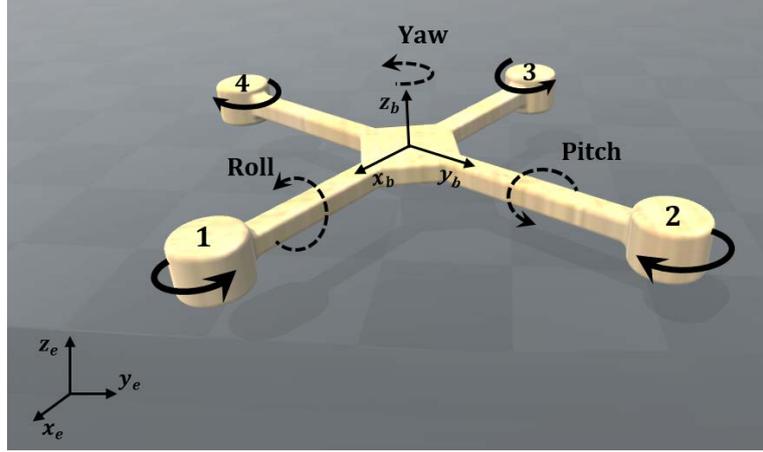
Figure 1. Quadrotor scheme

The quadrotor generally uses two pairs of rotors and to cancel the net moment along the z-axis, one pair (rotors 1 and 3) should rotate clockwise and one pair (rotors 2 and 4) counterclockwise. By changing the rotational speed of each rotor, the quadrotor supplants from a point to another through space. To make the y-axis torque and then the pitch angle (θ), one can augment the speed of rotor 3 and reduce the speed of rotor 1. This action causes the quadrotor to move along the x-axis. Likewise, to make the x-axis torque and then the roll angle (φ), one can augment the speed of rotor 2 and reduce the speed of rotor 4. This action also causes the quadrotor to move along the y-axis. Finally, to increase the z-axis torque and then the yaw angle (ψ), one can augment the speed of rotors 1 and 3 and reduce the speed of rotors 2 and 4.

To drive dynamic equations with respect to the earth frame, a rotation and a translational matrix should be used. The rotation matrix given by (1) is used to state linear velocities with respect to the earth frame. Also, the reverse translational matrix given by (2) is used to convert angular velocities with respect to the body-fixed frame to angular velocities with respect to the earth frame.

$$R = \begin{bmatrix} \cos\theta\cos\psi & \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ \cos\theta\sin\psi & \cos\varphi\cos\psi + \sin\varphi\sin\theta\sin\psi & \sin\theta\cos\varphi\sin\psi - \sin\varphi\cos\psi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{bmatrix}, \tag{1}$$

$$T = \begin{bmatrix} 1 & \tan\theta\sin\varphi & \tan\theta\cos\varphi \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi/\cos\theta & \cos\varphi/\cos\theta \end{bmatrix}, \tag{2}$$

The Newton-Euler equations given by (3) and (4) are used to drive the nonlinear dynamic model of the quadrotor.

$$F_{net} = \frac{d}{dt}[mV]_b + \Omega \times [mV]_b, \tag{3}$$

$$M_{net} = \frac{d}{dt}[I\Omega]_b + \Omega \times [I\Omega]_b, \tag{4}$$

The quadrotor is assumed to be symmetric inherent to the x and y-axis. It means that the center of gravity is located at the center of the quadrotor. Also, angles variations are small and the motor inertia is negligible rather than the quadrotor inertia. By considering these assumptions, the 6-DOF dynamic model with respect to the body-fixed frame can be expressed as Equations (5)-(10) [17-19].

$$\ddot{X} = \frac{1}{m} U_1 \left(cos\varphi \ sin\theta \ cos\psi + sin\varphi \ sin\psi \right),$$ (5)

$$\ddot{Y} = \frac{1}{m} U_1 \left(sin\theta \ cos\varphi \ sin\psi - sin\varphi \ cos\psi \right),$$ (6)

$$\ddot{Z} = \frac{1}{m} U_1 \left(cos\varphi \ cos\theta \right) - g,$$ (7)

$$\ddot{\varphi} = \frac{1}{I_{xx}} U_2 - \left(\frac{I_{zz} - I_{yy}}{I_{xx}} \right) \dot{\theta}\dot{\psi},$$ (8)

$$\ddot{\theta} = \frac{1}{I_{yy}} U_3 - \left(\frac{I_{xx} - I_{zz}}{I_{xx}} \right) \dot{\varphi}\dot{\psi},$$ (9)

$$\ddot{\psi} = \frac{1}{I_{zz}} U_4 - \left(\frac{I_{yy} - I_{xx}}{I_{zz}} \right) \dot{\varphi}\dot{\theta},$$ (10)

where m and I stand for the quadrotor's mass and inertia matrix respectively. Also, U_i is manipulated variable so that, U_1 is related to the thrust force, U_2 to the y-axis torque, U_3 to the x-axis torque, and U_4 to the z-axis torque. Basically, the quadrotor motion is achieved by changing the combination and varying the speed of the rotors described as Equations (11)-(14) [20].

$$U_1 = k_T(w_1^2 + w_2^2 + w_3^2 + w_4^2),$$ (11)

$$U_2 = k_T l(w_3^2 - w_1^2),$$ (12)

$$U_3 = k_T l(w_2^2 - w_4^2),$$ (13)

$$U_4 = k_D(w_1^2 - w_2^2 + w_3^2 - w_4^2),$$ (14)

where l, k_T, k_D, and w stand for the quadrotor's radius, thrust coefficient, drag factor, and propeller's speed respectively. Parameters m, I, and l are physical characteristics and k_T, k_D, and w are measured based on motor's property.

3. Control scheme

The quadrotor has four inputs and six coupled outputs and is considered as an under-actuated and highly nonlinear system. So a classical PID controller cannot handle is nonlinear inherent as it is expected. One solution is to use an adaptive algorithm that can adapt PID control in different modes. Here, a combination of ILA and enumerative learning algorithm is applied to select optimum gains for PID control somehow the error signals convergence to their minimum level.

3.1 Control system

Equation (15) is a general form of the control law for a classical PID controller:

$$U_i = K_P . e + \frac{1}{T_I} \int e\, dt + T_D \frac{de}{dt},\tag{15}$$

where K_P is the proportional gain, T_I is the reset time, T_D is the rate time, and e is the error signal.

ILA or iterative learning control (ILC) is an adaptive control method through which the performance of a control system becomes better and better as time increases and can improve tracking performance of a nonlinear system. This algorithm can perform well with the various types of controllers. Fuzzy control, neural network control, and genetic algorithm are some other methods that can improve PID control's performance more prices and faster than ILA. Equation (16) shows a general form of the control update law describing a PID-type ILA which includes parameters e, $\int e\, dt$, and $\frac{de}{dt}$.

$$G_{k+1}^i = G_k^i + \alpha^i . e_k^i + \beta^i \int e_k^i\, dt + \gamma^i \frac{de_k^i}{dt},\tag{16}$$

where α, β and γ are the learning rates. For a P-type ILA; gains   and   are equal to zero. To adapt the PID control gains, parameters K_P, T_I, and T_D are set as G each in a separate equation. Figure 2 shows the block diagram of a PID-type ILA.
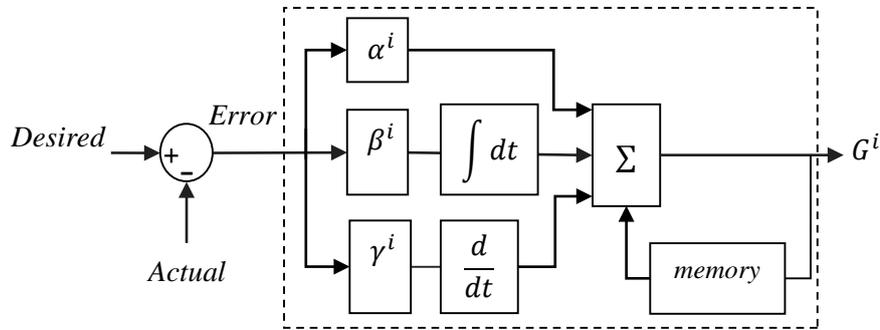

Figure 2. ILA block diagram

To tune the learning rates of ILA, an optimal method is used named as enumerative learning. In this method, a normalized boundary with specific steps selects for each parameter. Then the algorithm runs until the minimum total error is acquired and then the values in that step are saved as the optimal values for the learning rates. Finally, Figure 3 shows the overall block diagram of the proposed control system.
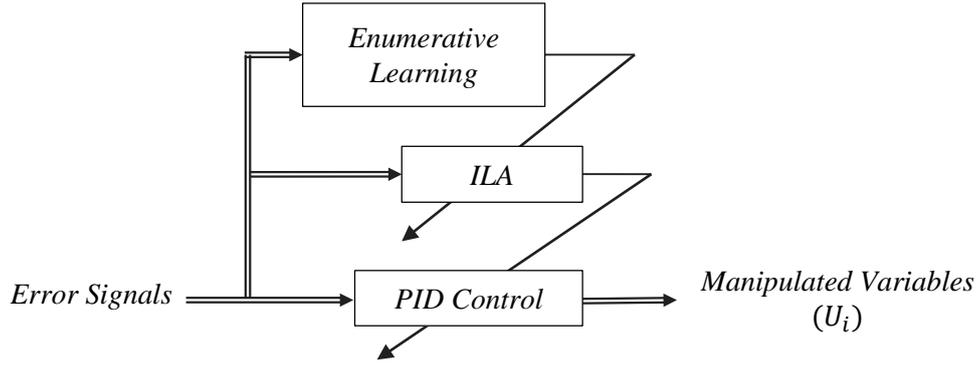
Figure 3. Control system block diagram

3.2 Control loops

Altitude and attitude control of the quadrotor is named as the inner control loop. For this part, a PID controller adapted by a PID-type ILA is employed for altitude control while a PID controller adapted by a P-type ILA is used for attitude control. The block diagram of the inner control loop and its input variables (error signals) and output variables (actual states) are shown in Figure 4.
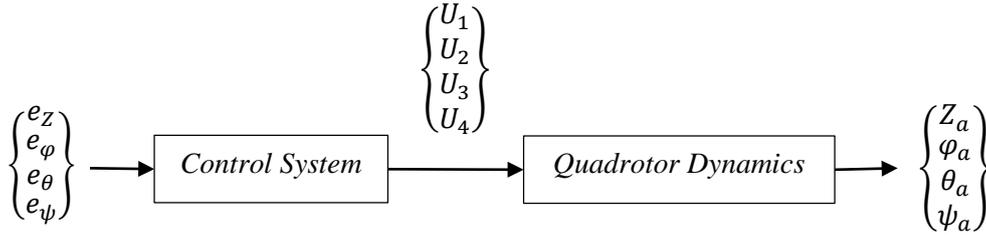

Figure 4. Inner control loop

Position control of the quadrotor is usually named as the outer control loop. For this part, a PID controller adapted by a PID-type ILA is employed for position control. The block diagram of the outer control loop and its input variables (error signals) and output variables (desired angles) are shown in Figure 5.
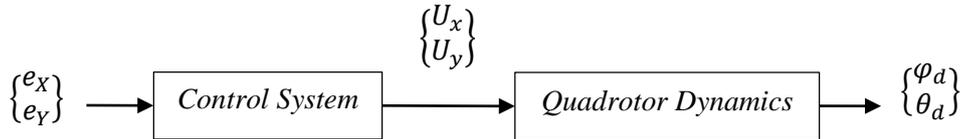

Figure 5. Outer control loop

where the relation between virtual forces U_x and U_y by the desired angles can be expressed as Equations (17) and (18) [20, 21].

$$U_x = cos\varphi \, sin\theta \, cos\psi + sin\varphi \, sin\psi, \tag{17}$$

$$U_y = sin\theta \, cos\varphi \, sin\psi - sin\varphi \, cos\psi, \tag{18}$$

4. Discussion simulation results

In this section, the performance of the proposed control method in trajectory tracking control is illustrated using Simulink MATLAB. The desired trajectories are selected as a circular path, a butterfly path, and a spiral path. Also for the simulation purpose, the imaginary quadrotor parameters are chosen as Table 1 [22].

Table 1. System Parameters for Simulation Purposes.

Parameter	Description	Value	Units
m	Quadrotor mass	0.14	kg
l	Quadrotor arm	0.17	m
I_{xx}	Inertia moment with respect to the x-axis	0.002	kg. m^2
I_{yy}	Inertia moment with respect to the y-axis	0.002	kg. m^2
I_{zz}	Inertia moment with respect to the z-axis	0.004	kg. m^2
g	Gravity acceleration	9.8	m. s^{-2}

The simulation result for tracking a circular path and its error signals (X_e, Y_e, Z_e) are shown in Figure 6. It can be seen that as time increases, the proposed controller is able to move the quadrotor to the desired path and minimize the error signals.
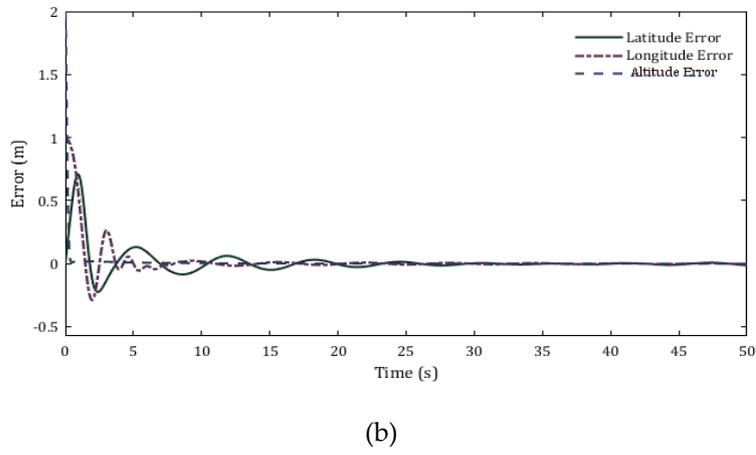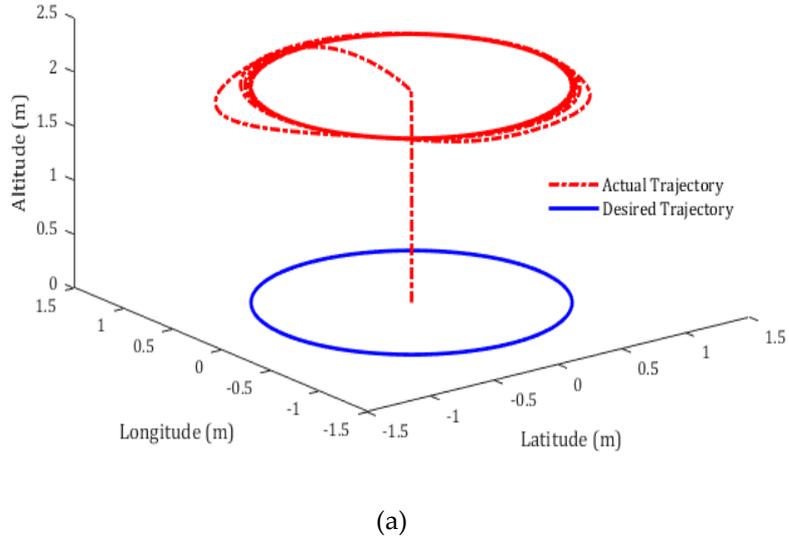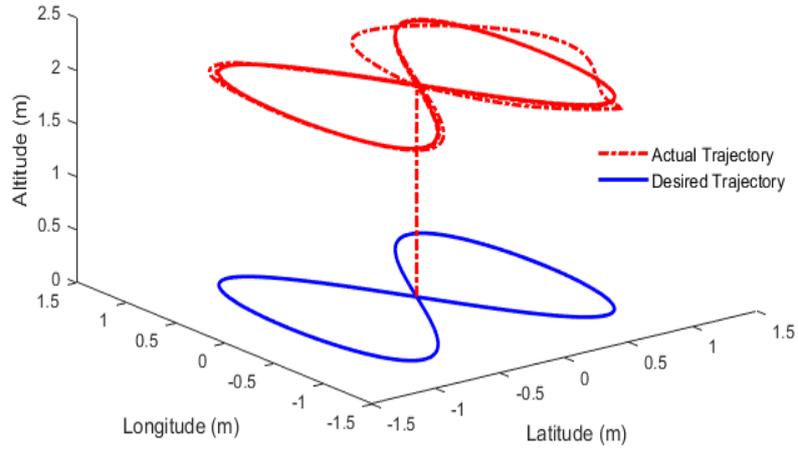
(a)

(b)

Figure 6. (a) Trajectory tracking control for a circular path; (b) Error signals

The simulation result for tracking a butterfly path and its error signals (X_e, Y_e, Z_e) are shown in Figure 7. Just like the circular path, it can be seen that the proposed controller is able to move the quadrotor to the desired path and minimize the error signals as time increases.
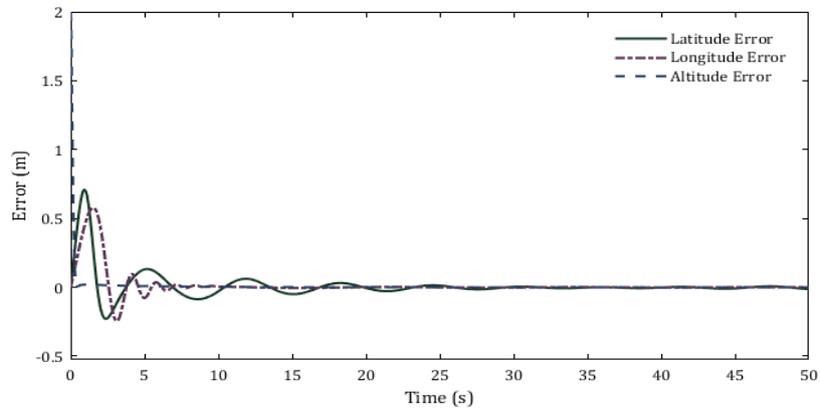
(a)

(b)

Figure 7. (a) Trajectory tracking control for a butterfly path; (b) Error signals

The simulation result for tracking a spiral path and its error signals (X_e, Y_e, Z_e) are shown in Figure 8. Usually, for tracking a trajectory, roll and pitch angles change and this change affects the total thrust which may cause instability. However, the proposed controller is able to move the quadrotor to the desired path and minimize the error signals as time increases.
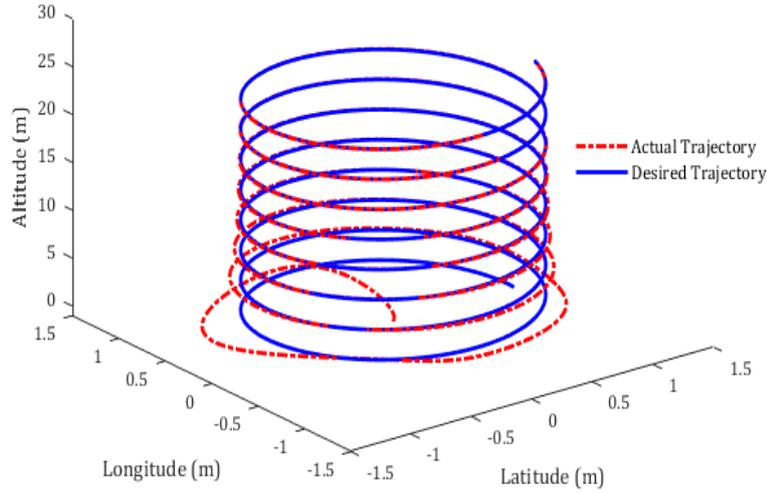
(a)
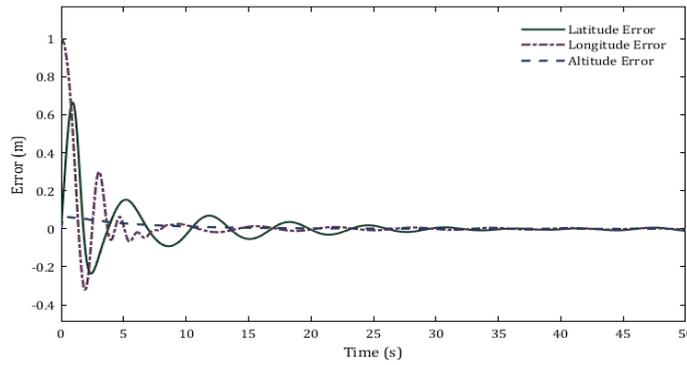
(b)

Figure 8. (a) Trajectory tracking control for a spiral path; (b) Error signals.

5. Conclusions

In this paper, an optimal ILA was presented to adapt PID control using the enumerative learning algorithm for the trajectory tracking control of a quadrotor. In this method, a PID controller adapted by the PID-type ILA was proposed for altitude and position control and a PID controller adapted by the P-type ILA was proposed for attitude control of a quadrotor. Also, the enumerative learning algorithm was used to choose the optimal values of the learning rates. For this purpose, at first, the dynamic model of the quadrotor was acquired based on the Newton-Euler equations. After that, the adaptive and optimal control system and the inner and outer control loops were defined. In the end, the simulation results for trajectory tracking of the quadrotor were demonstrated. Through simulation, it is concluded that as time increases, the performance of the suggested control method in trajectory tracking control becomes better and better and error signals convergence to zero. Future work in this area is to implement the proposed control method on an experimental model.

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