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Design of an Intelligent Controller for Station Keeping, Attitude Control, and Path Tracking of a Quadrotor Using Recursive Neural Networks

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ABSTRACT

During recent years there has been growing interest in unmanned aerial vehicles (UAVs). Moreover, the necessity to control and navigate these vehicles has attracted much attention from researchers in this field. This is mostly due to the fact that the interactions between turbulent airflows apply complex aerodynamic forces to the system. Since the dynamics of a quadrotor are non-linear and the system is a multivariable one, moreover, it has six degrees of freedom for only four control inputs, then it is an under actuated system. This is why conventional control algorithms employed to track desired trajectories of fully actuated aerial vehicles are no longer applicable for quadrotors. The main step in the manufacturing of a fully autonomous unmanned aerial vehicle is to design a controller which stabilizes the aerial vehicle in the presence of uncertainties and disturbances, then navigate it along a desired trajectory. The aim of this study is to design and implement an intelligent controller for station keeping, attitude control, and path tracking of a quadrotor. For this purpose, an artificial neural network method was employed. The artificial neural network is one of the most powerful and useful tools in the modification of a control system. In this study, the control methods conventionally applied to quadrotors are reviewed at first. Then, in order to analyze the behavior of the system and also to design the controller, the state equations of a quadrotor are discussed. Following that, the design of a recurrent neural network based non-linear PID control algorithm is presented. Finally, the results of the simulation performed are presented, and the performance of the proposed algorithm are investigated. It was shown that by using the proposed algorithm, the quadrotor tracks the desired trajectory, and simultaneously, its attitude is stabilized.

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1. INTRODUCTION

The interest in unmanned aerial vehicles (UAVs) has grown dramatically in recent years. Moreover, the necessity to control and navigate these vehicles has attracted much attention from researchers to this field. Applications for a UAV include road traffic management, mapping, tracking, search and rescue, exploration, inspector of borders and impassable areas, etc. [1, 2]. The application of UAVs is very important where a human presence is hazardous. Among all kinds of UAVs, the capability to maintain a hover at a desired position, and also takeoff and landing in congested spaces makes a vertical take-off and landing (VTOL) aircraft more suitable for verity of applications. Moreover, among all kinds of VTOL aircraft, mechanical simplicity and ease of control of quadrotors make their use advantageous over traditional single rotor helicopters and expensive rotorcrafts (Figure 1). All six degrees of freedom (DOF) of quadrotors are controlled through these four rotors. In addition, when compared with other rotorcrafts, quadrotors are able to carry heavier loads. The main disadvantage of quadrotor is its high-energy requirement, which in turn decreases the total flight time of quadrotor [3].

The motion of quadrotors could be an interesting and challenging research topic, mostly due to the fact that the

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Figure 1. Schematic of a quadrotor

interactions between turbulent airflows apply complex aerodynamic forces to the system. From the control point of view, a quadrotor is a highly nonlinear, multivariable, and underactuated system which has six degrees of freedom and only four actuators. This is why conventional control systems employed to track desired trajectories of fully actuated aerial vehicles are no longer applicable for quadrotors. It should be noted that the design of a controller which stabilizes the aerial vehicle in the presence of uncertainties and disturbances, then navigate it along a trajectory, is the main step in the manufacturing of a fully autonomous UAV. Recently, considerable research has been devoted to the quadrotor as a certain kind of UAVs. Among various factors, station keeping, attitude control, and path tracking of quadrotors are of great importance [4].

Several traditional linear control techniques have been developed and tested on quadrotors. However, this kind of controllers is designed based on a linearized model of the system; therefore, resulting approximations are only valid in a small region around an operating point. Therefore, these controllers are not efficient enough when the system accompanied by some uncertainties. In other words, linear controllers are unable to compensate non-linear behaviors of the system, so it seems that these controllers are not appropriate choices for station keeping and attitude control of quadrotors. Therefore, it is inevitable to use nonlinear model-based controls. By designing a suitable nonlinear controller for a VTOL aircraft, it is possible to improve the performance and stability margins in a real aerial vehicle. It should also be noted that a nonlinear controller has to show better performance in the presence of uncertainties, environmental perturbations, and nonlinear phenomena occurring in the system. The backstepping control technique introduced in [5] has a better performance compared with the Linear-Quadratic Regulator (LQR) method. One of the control methods based on linearization is feedback linearization [6]. One of the advantages of this technique is that the designed controller is independent of a particular operating point. According to [7], it is impossible to linearize the nonlinear model of quadrotor using the static feedback control law, then to solve the problem of underactuated operation of the system. So, it is preferred to employ a dynamic feedback controller. Using this kind of controller, the closed-loop system transforms into a linear, controllable system for input and output. The feedback linearization controller combining with sliding mode controller proposed in [6] and a sliding mode observer proposed in [8], all helped maintain asymptotic stability in the presence of external disturbances. Other methods like pole placement for attitude control [9] and velocity control [10] have also been used.

The third kind of controllers designed for quadrotors is robust controllers. Using this kind of controllers, is possible to overcome the external disturbances and uncertainties. Linear methods are an example of these controllers, which was proposed in [11]. In [12], a hybrid method that combines Model Base Predictive Control (MPC) and linear H∞ robust control was employed. H∞ robust control was used to achieve robust stability, while Model Base Predictive Control was used as a path-tracking controller.

In recent years, with dramatic improvements in novel control technologies, it seems necessary to develop accurate, swift, and robust control methods [13–15]. Aforementioned control methods have been widely used in previous researches. However, as mentioned above, using these methods necessitates dynamic linearization of the system, which in turn decreases its robustness and maneuverability considerably. Moreover, all these methods require a precise understanding of the dynamics of the system to linearize it or to adjust controller parameters to achieve a desired result. As a system becomes more complicated, it influenced by more phenomena, some of which are unknown. Therefore, resulting mathematical model would only be an approximation of a real system. This introduces some uncertainties to the system. However, a full nonlinear uncertain model of quadrotor has to ensure the robustness and efficiency of the system in the presence of uncertainties and disturbances. This is why there is a growing interest in research for smart controllers. Neural network based control is a typical example of a smart controller. Artificial neural networks are one of the most powerful and useful tools in the modification of a system. In this article, we will use neural network method for station keeping and path tracking of a quadrotor in the presence of environmental perturbations. This method has several advantages as follows:

- multiple-input, multiple-output systems can be easily controlled through the method,
- using this control method makes it possible to easily achieve a desired position while maintaining the stability of UAVs,
- In comparison with existing control methods, neural network method is capable of accommodating a larger number of uncertainties.

Accordingly, the aim of this study is to design and implement a neural network controller for station keeping and path tracking of a quadrotor. Section 2 provides an introduction to an appropriate model that can be used to analyze the behavior of the system and also to design the controller. Section 3 describes the control algorithm. In section 4, the designed controller will be applied on a real quadrotor in the presence of uncertainties and variations and its performance will be evaluated. Finally, a conclusion will be presented.

2. EQUATIONS OF MOTION

As mentioned in previous sections, design a suitable controller requires a thorough understanding of the behavior of the aerial vehicle. Here, with the behavior of the system, we mean its dynamics. According to previous researches, dynamics of the aerial vehicle discussed here can be obtained using Newton-Euler formulation. It is important to consider all forces and torques applied on the aerial vehicle. The motion of an aerial vehicle in three-dimensional space has six degrees of freedom (DOF). Therefore, six degrees of freedom need to describe the motion of an aerial vehicle. In this section, we will use six dynamic equations describing the behavior of the aerial vehicle, along with kinematic equations defining the attitude of quadrotor with respect to a reference frame (i.e. reference station and reference attitude) to describe the motion of quadrotor. In order to use the Newton-Euler formulation, an inertial coordinate system and body coordinate system will be employed. Similar to other aerial vehicles, aerodynamic forces, thrust force, and gravitational force should be taken into account in quadrotors. It should be noted that designing an efficient control system requires a precise understanding of the dynamics of all components of the system. This is why considering the dynamics of actuators is important.

Quadrotor consisting of four rotors in a cross configuration. Sensors, central processing unit, controller, camera, etc. are all located at the center of the quadrotor. Four brushless DC motors (BLDC) are arranged at the corners of a square body. Each of BLDCs has a lightweight propeller. Generally, BLDC and blade are considered together and referred to as a rotor. It is worth noting that in the current research, only the rpm of BLDCs have been taken as the input of the controller.

Flight maneuvers become possible through varying the revolutions per minute (rpm) of rotors. During vertical movements like take off and hovering, consequent lift force applied from rotors is in a vertical direction and against the direction of gravitational force. In order to prevent the quadrotor from rotating about the axes of the main body, all rotors must apply the same lift force. Then, vertical movement of quadrotor occurs by equally changing rotor angular speeds. In a quadrotor, two adjacent motors spin in the opposite direction, while two opposite motors spin in the same direction. Pitch movement (θ) or rotating about y-axis is acquired by increasing (decreasing) back rotor velocity and decreasing (increasing) front rotor velocity. Roll movement (ϕ) or rotating about x-axis is acquired in the same manner, but using adjacent motors. Yaw movement (ψ) or rotating about a vertical axis is acquired by increasing the angular velocities of two opposite rotors and decreasing the velocities of the other two (Figure 2). Usually, such a motion is accompanied by keeping total thrust force of rotors constant. Figure 2 shows a schematic representation of these movements.

Generally, during maneuver action, quadrotor has an inclined moving in the direction of the rotor having the slowest velocity. As a result, thrust force gets an additional component in that direction, causing quadrotor to have translational motion. In other words, such a structure has a variable coupling between the axes, so as the quadrotor cannot have a translational motion unless under the conditions of roll or pitch movements. In fact, a variable coupling between the axes allows to control six degrees of freedom using four controlling inputs. Vertical movement occurs by changing rotor angular speeds. The way how these maneuvers occur is presented in Figure 3 [16].

3. DYNAMIC MODELING OF AN AERIAL VEHICLE

In this research, Newton-Euler formulation along with momentum theory is used to obtain dynamic equations of

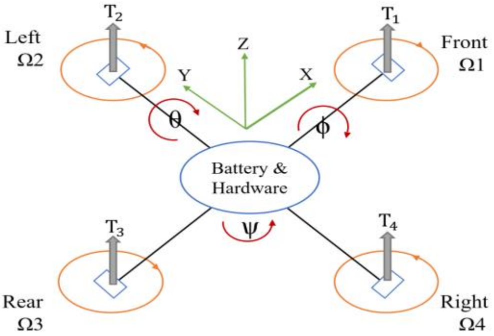

Figure 2. A simple quadrotor diagram [16]

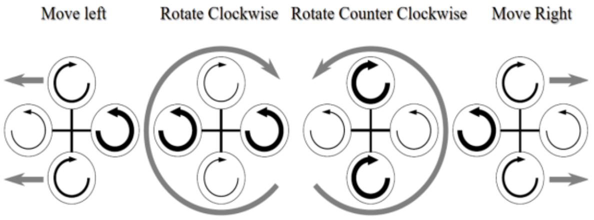

Figure 3. Basic motion of a quadrotor (Arrow width is proportional to rotor angular velocity) [16]

the quadrotor. In dynamic modeling of quadrotors, the following assumptions are commonly made:

- Quadrotor has a rigid frame,
- Quadrotor has a symmetrical frame,
- Propellers are considered to be rigid, then flapping does not occur,
- The origin of body-frame Cartesian coordinates is centre of mass of the quadrotor,
- Body frame axes are coincident with main inertial axes of the quadrotor. As a result, the matrix I becomes a diagonal matrix. This makes equations simpler,
- Thrust and drag both are proportional to the squared velocity of the propeller.

Unlike conventional rotorcrafts, controlling roll, pitch, and yaw angles in quadrotors is performed through simple mechanisms. A combination of these three angles is used to adjust the overall behavior of quadrotor, therefore the calculation and control of the angles are of great importance. The process of monitoring and tracking the angles during the motion of quadrotor requires using two different coordinate systems as follows (see Figure 4):

- The earth-fixed frame (E-frame) ,
- The body-fixed frame (B-frame).

In order to obtain equations of motion, Newton's laws of motion have to be employed. The point is that this law is only valid for the inertial frame of reference. In the body-fixed frame, the inertial matrix remains unchanged over time.

In order to acquire a model that evaluates the behavior of the system, its cinematic and dynamic equations should be driven. Cinematic equations define rigid frame without considering the forces and torques stimulating motion. A cinematic description is a geometric description. On the other hand, dynamic equations present an appropriate map projection for external forces applied on the quadrotor, and its station, velocity, and acceleration. It has been proposed that the dynamic modeling of quadrotors can be performed in two ways. The first method is based on the Lagrange formulation, while the second method is based on the Newton-Euler formulation. Considering that the aim of this research is to design a controller, modeling equations have been borrowed from [16, 17]. The model used in these references have been extracted from the Newton-Euler formulation.

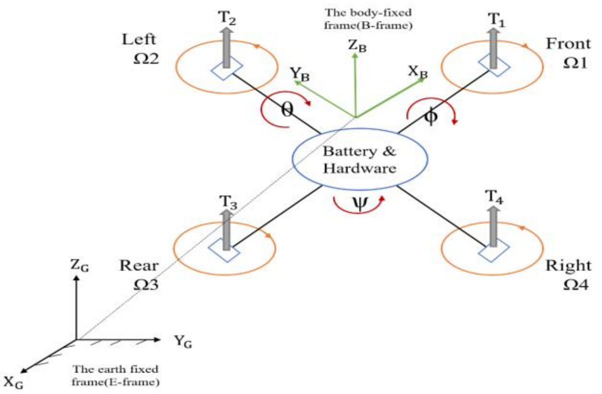

Figure 4. Schematic of the inertial reference frame and the body fixed reference frame for a quadrotor

The motion of a rigid body in three-dimensional space has six degrees of freedom (DOF). Three of these six degrees of freedom define the center of mass (COM) of moving object, while others define the orientation of the object in the space. Considering the fact that each degree of freedom involves two state variables, namely station and velocity, a set of twelve differential equations is required to describe the motion of a rigid body. Using the relationship between forces and torques, one can develop equations of motion in the inertial coordinate system [16, 17]. Equations of angular acceleration can be written as:

$$\begin{aligned}
\ddot{\phi} &= \dot{\theta}\dot{\psi}\frac{I_Y-I_Z}{I_X} - \frac{I_R}{I_X}\dot{\theta}\Omega_R + \frac{lb}{I_X}u_1 \\
\ddot{\theta} &= \dot{\phi}\dot{\psi}\frac{I_Z-I_X}{I_Y} + \frac{I_R}{I_Y}\dot{\phi}\Omega_R + \frac{lb}{I_Y}u_2 \\
\ddot{\psi} &= \dot{\theta}\dot{\phi}\frac{I_X-I_Y}{I_Z} + \frac{d}{I_Z}u_3
\end{aligned} \tag{1}$$

where (ϕ,θ,ψ) represents Euler angles (roll (ϕ), pitch(θ), and yaw(ψ)) in the inertial coordinate system. Moreover, (I_X, I_Y, I_Z) represents the moment of inertia around X, Y, Z axes, respectively. It is also supposed here that quadrotor has a symmetrical frame, i.e. $(I_{XY} = I_{YZ} = I_{ZX} = 0)$. In the aforementioned relations, Ω_R implies the total angular velocity of rotors. $u_i, i = 1,..,4$ are controlling inputs. Therefore, the equations related to the translational acceleration of the aerial vehicle can be presented as follows [16]:

$$\begin{aligned}
\ddot{X} &= sin(\theta)\, cos(\phi)\, \frac{b}{m}u_4 \\
\ddot{Y} &= -sin(\phi)\frac{b}{m}u_4 \\
\ddot{Z} &= -g + cos(\theta)\, cos(\phi)\frac{b}{m}u_4
\end{aligned} \tag{2}$$

In Equation (2), (X,Y,Z) represents the station of quadrotor in the inertial coordinate system, m is the total mass of quadrotor, g is gravitational acceleration, b is thrust coefficient, and l is the distance from the center of a rotor blade to the center of the body.

In order to simplify Equations (1) and (2) and to rewrite them as state equations, change of variables and some simplifications were done as follows:

$$\begin{aligned}
&x_1 = \phi \quad x_2 = \dot{\phi} \quad x_3 = \theta \quad x_4 = \dot{\theta} \\
&x_5 = \psi \quad x_6 = \dot{\psi} \quad x_7 = X \quad x_8 = \dot{X} \\
&x_9 = Y \quad x_{10} = \dot{Y} \quad x_{11} = Z \quad x_{12} = \dot{Z} \\
&x_5 = \psi \quad x_6 = \dot{\psi} \quad x_7 = X \quad x_8 = \dot{X}
\end{aligned} \tag{3}$$

With constant parameters:

$$
\begin{aligned}
&a_1 = \frac{I_Y - I_Z}{I_X} \quad a_2 = \frac{I_R}{I_X} \quad b_1 = \frac{lb}{I_X} \\
&a_3 = \frac{I_Z - I_X}{I_Y} \quad a_4 = \frac{I_R}{I_Y} \quad b_2 = \frac{lb}{I_Y} \\
&a_5 = \frac{I_X - I_Y}{I_Z} \quad b_3 = \frac{d}{I_Z} \\
&b_4 = \frac{b}{m}
\end{aligned} \tag{4}
$$

Finally, using the change of variables presented in Equation (4), we can write equations of motion in state space as $\dot{X} = f(X, U)$, where U represents the vector of controlling inputs and X is state vector which is defined as follows [16]:

$$
\begin{aligned}
&\dot{\mathrm{X}} = [X, \dot{X}, Y, \dot{Y}, Z, \dot{Z}, \emptyset, \dot{\emptyset}, \theta, \dot{\theta}, \psi, \dot{\psi}] \\
&\mathrm{U} = [u_1, u_2, u_3, u_4]
\end{aligned} \tag{5}
$$

In Equation (5), controllers can be defined as a function of rotor velocity as follows:

$$
\mathrm{U} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \tag{6}
$$

$$
\Omega_R = (-\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4) \tag{7}
$$

In Equation (6), u_1, u_2, u_3, and u_4 represent roll torque, pitch torque, yaw torque and thrust force, respectively. Finally, equations can be written in the form of $\dot{\bar{X}} = f(\bar{X}, \bar{\mathrm{U}})$ as follows:

$$
\begin{aligned}
&\dot{x}_1 = x_2 \\
&\dot{x}_2 = x_4 x_6 a_1 - a_2 x_4 \Omega_R + b_1 u_1 \\
&\dot{x}_3 = x_4 \\
&\dot{x}_4 = x_2 x_6 a_3 + a_4 x_2 \Omega_R + b_2 u_2 \\
&\dot{x}_5 = x_6 \\
&\dot{x}_6 = x_2 x_4 a_5 + b_3 u_3 \\
&\dot{x}_7 = x_8 \\
&\dot{x}_8 = \sin(x_3) \cos(x_1) b_4 u_4 \\
&\dot{x}_9 = x_{10} \\
&\dot{x}_{10} = -\sin(x_1) b_4 u_4 \\
&\dot{x}_{11} = x_{11} \\
&\dot{x}_{12} = -g + \cos(x_3) \cos(x_1) b_4 u_4
\end{aligned} \tag{8}
$$

As it was mentioned before, the control problem discussed here is station keeping and attitude control of quadrotor. The equations of the system were defined in the previous sections. In the next section, we will try to develop an appropriate and applicable control for this system defined with Equation (8).

4. CONTROL ALGORITHM

Although the control structure and control inputs are mainly dependent to the control method applied, however, in order to control a dynamic system, it is essential to have sufficient information about its behavior. Usually, the first step in the design process for a control system is to develop a mathematical model. As the resulting mathematical model becomes a more reasonable approximation of a real quadrotor, the control model designed based on this model shows a better performance.

However, it should always be taken into account that the parameters of a modeled system may contain some errors, or are only an approximation of reality.

The unreliability of mathematical models describing dynamic systems mainly arises from two types of uncertainties which include:

- Structured (parametric) uncertainty, which arises from uncertainties accompanied with the values of model parameters,
- Unstructured uncertainty, which arises from model simplification.

As previously mentioned, regardless of what kind of control method is employed, it is essential to have sufficient information about the system.

In addition, using most of the advanced control methods requires obtaining an accurate mathematical model. In other words, an accurate mathematical model leads to a suitable control of the system by using approaches employed in advanced control methods. On the other hand, an inaccurate mathematical model does not only lead to a suitable control of the system, but also introduces some uncertainties to a closed loop system, which makes the system unstable.

Despite advanced control systems, smart controllers do not have such a disadvantage. This means that the smart control systems can show desirable performance, even when the mathematical model is not accurate. This advantage of smart controllers encourages researchers to introduce a new concept in the design of control structures named “smart robust control approach (i.e. approaches based on neural networks) [18, 19].

A noise robust control system is one which reacts intelligently to external disturbances, meaning neutralizes or diminishes the detrimental effects from these disturbances. In addition, a parameter robust control system is one which is robust to structural uncertainties, parametric uncertainties, or un-modeled uncertainties. A system having advantages of both noise robust control system and parameter robust control system is a smart robust controller. The aim of the current study is to develop such a controller.

This study is aimed to design a smart robust controller to navigate the aerial vehicle along its desired trajectory.

Navigation of aerial vehicles can be performed in two ways. One method is done by a human operator who controls the flight via a remote. On the other hand, the Navigation process is fully autonomous and is performed using a programmable algorithm in the internal processor of the aerial vehicle. In both methods, monitoring system navigates the aerial vehicle towards a desired trajectory by sending appropriate parameters to the controller. In this paper, the suitable controller for the aerial vehicle will be designed through the control of station vector, linear velocity, and yaw rotation angle of the aerial vehicle, according to the algorithm shown in Figure 5.

It is obvious from the dynamic structure of quadrotors that in order to acquire a translational motion in longitudinal and transversal directions, it is required to rotate the aerial vehicle about its main axes. This requirement arises from the fact that the lift force applied to the main body of the quadrotor is vertical. Once the quadrotor deviates from its equilibrium state, decomposes longitudinal and transversal components, then the translational motion in these directions becomes possible. According to Equations (1) and (2) presented in Section 1, attitude equations (rotational) and roll, pitch, and yaw angles are independent of station parameters, while station equations are dependent on the rotational angles of the system. In other words, in order to produce a translational motion in the system, its rotational angles should be changed. The motion mechanism of a quadrotor is such that the translational motion in longitudinal and latitude directions is obtained by varying roll and pitch angles.

Considering the aim of the present study, i.e. station keeping and attitude control of quadrotor, the desired pitch and roll angles cannot be arbitrarily determined, so the controller should be designed in such a way that the desired roll and pitch angles could be determined using the deviation of the path in which the quadrotor travels from the desired path. Therefore, a double-loop control mechanism including an inner and an outer loop has been designed for control implementation. Control of linear velocity of the aerial vehicle and determining the desired roll and pitch angles are performed in the outer loop, while control of rotational angles and achieving their desired values are performed in the inner loop. Figure 6 shows a schematic representation of the designed control system. Controllers employed in this paper is a modified non-linear PID which is based on recurrent neural networks concept. This concept will be described later in detail.

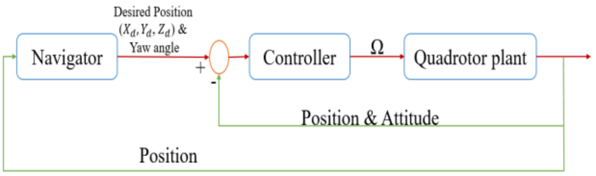

Figure 5. Coupling diagram of position and attitude subsystems

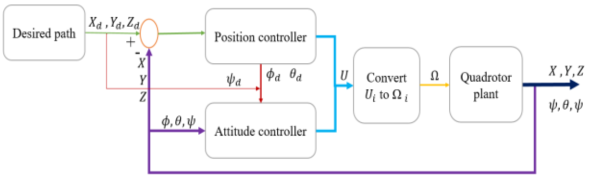

Figure 6. Coupling diagram of position and attitude subsystems

According to Figure 6, the values of the outer loop should be determined first. With the aim of controlling the station of quadrotor in the horizontal plane by controlling its linear velocity, determining the desired roll and pitch angles is performed in the outer loop.

In other words, horizontal motion is conducted by inclining trust vector towards the direction of travel. Such a motion is made possible by rotation of the quadrotor. In fact, the station keeping to reach the desired X and Y p positions is achieved by taking appropriate roll and pitch angles. Therefore, the first step in the model designed here is to determine reference roll and pitch angles (ϕ_d, θ_d), which can be obtained from Equations (9) to (11). According to Equation (2), we have [15]:

$$\phi_d = -\sin^{-1}\left(K_{1Y}(Y_d - Y) + K_{2Y}(\dot{Y}_d - \dot{Y})\right) \tag{9}$$

Similarly:

$$\theta_d = \sin^{-1}\left(\frac{K_{1X}(X_d - X) + K_{2X}(\dot{X}_d - \dot{X})}{\cos(\phi)}\right) \tag{10}$$

In Equations (9) and (10) K_{1X}, K_{2X}, K_{1Y}, and K_{2Y} are positive constant gains and are obtained by trial and error and modification methods. The rate of changes in roll and pitch angles can be determined from Equations (11) and (12) [15].

$$\dot{\phi}_d = \frac{K_1 \times \dot{Y} + K_2 \times \ddot{Y}}{\sqrt{1 - (K_1 \times Y + K_2 \times \dot{Y})^2}} \tag{11}$$

Similarly:

$$\dot{\theta}_d = \frac{-\left(\frac{K_1\dot{X} + K_2\ddot{X}}{\cos(\phi)} + \frac{(K_1 X + K_2\dot{X})\dot{\phi}\sin(\phi)}{\cos^2(\phi)}\right)}{\sqrt{1 - \frac{(K_1 \times X + K_2 \times \dot{X})^2}{\cos^2(\phi)}}} \tag{12}$$

We determined the appropriate roll and pitch angles to reach desired X and Y positions. Now, if we show the vector of variables of the desired state with X_d, then:

$$\begin{aligned}
&\mathrm{X}_{1d} = \phi_d, \quad \mathrm{X}_{2d} = \dot{\phi}_d \\
&\mathrm{X}_{3d} = \theta_d, \mathrm{X}_{4d} = \dot{\theta}_d \\
&\mathrm{X}_{5d} = \psi_d, \mathrm{X}_{6d} = \dot{\psi}_d \\
&\mathrm{X}_{7d} = X_d, \mathrm{X}_{8d} = \dot{X}_d \\
&\mathrm{X}_{9d} = Y_d, \quad \mathrm{X}_{10d} = \dot{Y}_d \\
&\mathrm{X}_{11d} = Z_d, \mathrm{X}_{12d} = \dot{Z}_d
\end{aligned} \tag{13}$$

Now, it is possible to determine the deviation of angles and stations from their desired values as a function of reference values. Then we will try to control the quadrotor by using a neural network based non-linear PID method.

5. NEURAL NETWORKS

The artificial neural network (ANN) makes it possible to process and learn simultaneously. This is why the ANN is one of the most powerful and useful tools in optimization processes. Depending on the structure of the network and the way in which processing elements are combined, ANNs have extensively been used in different applications such as modeling of the mind, time series forecasting, optimization, and control systems. In order to employ an ANN in these applications, it is required to develop a mathematical model. A simple mathematical model for an ANN is shown in Figure 7 [20].

In Figure 7, x, W, b, and f are vector of inputs, vector of weights, bias value, and the assumed function for neuron (which can be assumed to be either linear or non-linear), respectively. The neural network based model output can be represented by Equation (14):

$$y(k) = f(\sum_{i=1}^{n} W_i \times x_i(k) + W.b) \tag{14}$$

Depending on the activity for which the ANNs are designed, the output function can be linear, logarithmic, or tangent. The most important advantage of nonlinear functions over their linear counterparts is that nonlinear functions update weights slowly, which in turn makes the system robust against abrupt variations. The current research aims to employ ANNs to achieve station keeping and path tracking of a quadrotor. The control structure proposed to achieve a smart controller is given in Figure 8.

According to the proposed control structure in Figure 8, the artificial neural unit determines the control coefficients based on the current station and attitude of the quadrotor and sends them to the controller unit. Using the PID algorithm and based on the received coefficient from the artificial neural unit, the controller unit calculates control commands.

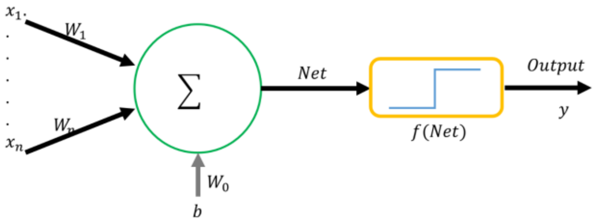

Figure 7. Schematic of a simple mathematical model for an ANN

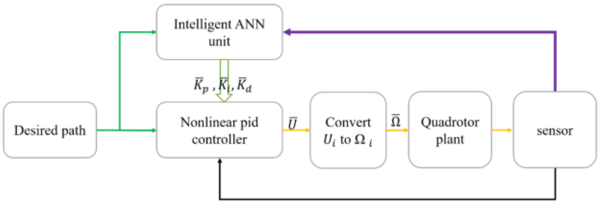

Figure 8. The structure of the proposed controller

It should be noted that the PID controller is a feedback controller with a simple structure and good performance. In this study, we will employ such a controller to reduce the deviation between the measured outputs and the desired trajectory. This controller consists of three parameters which are constants; however, in this research, they are assumed as variables. These parameters will be continuously updated using the neural network. Generally, this controller is called a three-term controller. In other words, a PID controller consists of three individual units: P, I, and D imply the proportional, integral and derivative modes of the controller, respectively. P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on the rate of error variations. Following, design and implementation procedure of the proposed algorithms are described.

6. DESIGNING A SMART NONLINEAR PID CONTROLLER

In this section, we will employ a PID controller for station keeping, attitude control of the quadrotor. As it was mentioned in section 4, the position of quadrotor along the *X* and *Y*-direction depends on ϕ and θ angles. On the other hand, the yaw angle is independent of other variables, so should be controlled independently. Then, it is required to design four control functions to satisfy the aim of station keeping, attitude control of the quadrotor. The control framework assumed to satisfy these aims is a nonlinear smart PID controller which is based on an ANN. We will use a PID controller to control each of (ϕ, θ, ψ) and (Z) variables. The coefficient of each controller is continuously updated using the neural network, as shown in Figure 8. Here, ANN, as a smart monitoring unit, collects input/output pairs and determines the control coefficients autonomously based on the changes occur in the system. Since there are four variables, and each variable needs three control coefficients (kp, ki, kd), then three neural networks were designed to update coefficients.

Each network receives the error and corresponding error rate as the inputs (eight inputs) and renders the coefficients as the outputs (four outputs). Figure 9 shows these inputs and outputs.

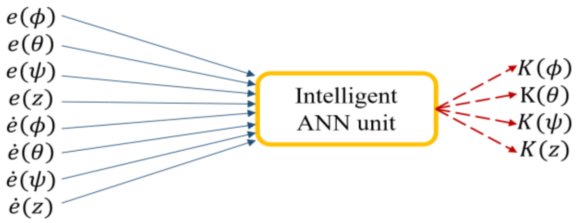

Figure 9. Inputs and outputs of the proposed network, K indicates control coefficients

Initially, the ANN learns how to change the coefficients, while the robustness of the system is maintained. Then, the control unit updates these coefficients efficiently so that the controller renders the most suitable values and tracks the desired path accurately with a minimum deviation. The proposed ANN structure used for online adjustment of PID controller is demonstrated in Figure 10. This network is in fact a multilayer recurrent network which consists of eight inputs (i.e. error and error rate), five neurons as a hidden layer, and other four neurons as an output layer (or control coefficients).

Recurrent networks have numerous applications in different scientific fields. There are two kinds of these networks: Elman network and Hopfield Network. An Elman network is a multilayer network along with a feedback from the output of the hidden layer to its input. This feedback helps the network to recognize short-term and time-dependent patterns. In addition, a Hopfield network is used to save one or more stable object vectors. One can assume these stable vectors as memories which can be remembered by the network once it receives an identical input. In MATLAB software, Elman networks are produced using the newelm command function, while Hopfield Networks are produced using the newhop command function.

In this research, the Elman network has been employed. Commonly, Elman networks consist of two layers and have a feedback from the output of the hidden layer to its input. In their hidden and output layer, Elman networks use tansig neurons and purelin function, respectively. This particular combination in double layer networks makes it possible to estimate a function with infinite number of discontinuities. To this purpose, the network needs to contain sufficient neurons in its hidden layer. Using more neurons in this layer increases its coincidence with the desired function. The main difference between these networks and conventional double-layer networks lies in the fact that the former includes a feedback in their structure. The delay presents in this feedback causes the data obtained from the previous step to be transferred to the network during the current step. Then if we have two Elman networks with the same weights and biases, and they receive specified input in a specified time step, they may still have different outputs. This arises because of the difference in the feedback states. Figure 10 shows the training error curve for the trained network proposed for K_p coefficients.

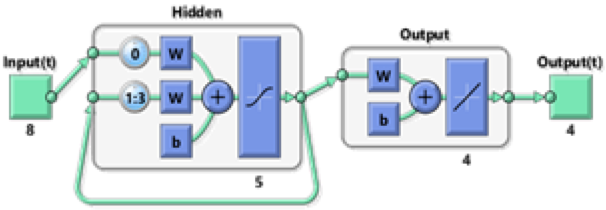

Figure 10. The structure of the ANN proposed in this study

After training the network, it was saved as a control coefficients predictor function. Figure 11 shows the average variation of the squared output error for K_p coefficients in a trained network. As can be seen, at the end of epoch 39, the best training performance for predicting the network is 0.00042166. It should however be noted that it is still possible to train the network through other methods and obtain more desirable results.

Figure 12 shows the error histogram diagram for the trained network. In the histogram diagram shown in Figure 12, as the increased frequency of the trained data errors around the zero line (identified in orange), indicates that the training of the network is more efficient. As can be seen in the histogram, the highest frequency is concentrated around the zero line, which indicates the desired training procedure has been done.

Since the designed controller has three coefficient (k_p, k_i, k_d), then it is required to design three networks input and output of which are error /error rate and desired coefficients, respectively. Therefore, it is required to design, train, and implement three networks separately. Here, only results obtained from training network k_p are presented (Figures 11 and 12). Following, the results obtained from implementing the control algorithm designed for station keeping and attitude control is presented.

7. SIMULATION RESULTS

As it was mentioned in the previous section, three

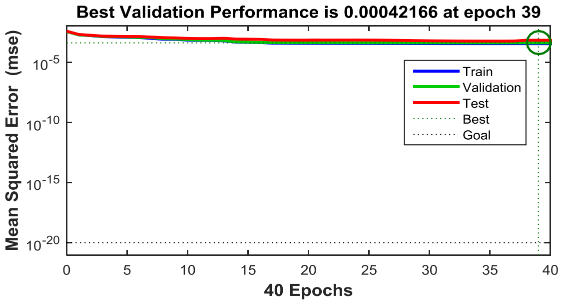

Figure 11. The training error curve for the trained network

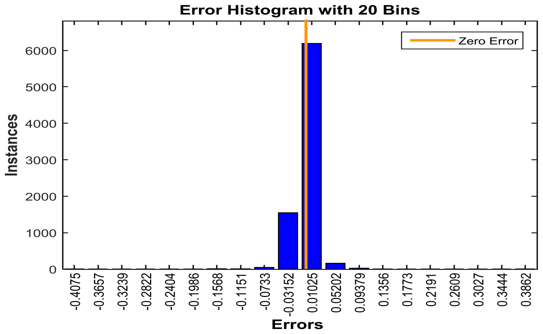

Figure 12. The error histogram diagram for the trained network

networks have been designed and trained separately. In the next subsections, we will first implement the algorithm designed for station keeping and attitude control of a special model of quadrotor, and then, using simulation, we will try to evaluate its performance. The physical parameters of the quadrotor obtained from [14, 15] are given in Table 1.

7. 1. Simulation Results in Terms of the Attitude Control of Quadrotor

Here, the attitude control of the UAV using the proposed intelligent control method is discussed. For this purpose, the initial values of the system angles have been considered as Equation (15). It should be noted that in this section we aim to achieve system stability, altitude stability, and the desired null values of the angles. The initial altitude of the UAV is:

$$\emptyset(0) = \frac{\pi}{3}, \theta(0) = -\frac{\pi}{4}, \psi(0) = \frac{\pi}{6} \quad (15)$$

Figure 13 demonstrates the variations of the roll, pitch and yaw angles. The curve depicted in this figure makes it possible to investigate the stability of the rotational attitude of the quadrotor. As can be seen, it takes less than two seconds for roll, pitch and yaw angles to reach their desired values. Afterward, the rotational attitude of the quadrotor becomes stable.

TABLE 1. Constants of the model used in this study

No.	Physical parameter	Unit	Values
1	length of moment arm (l)	Meter (m)	0.232
2	Mass (m)	Kilogram(kg)	0.52
3	Trusr factor (b)	$N.s^2$	$3.13e^{-5}$
4	Drag factor (d)	$N.s^2$	$7.5e^{-7}$
5	x-axis inertia (Ix)	$kg.m^2$	$6.228e^{-3}$
6	y-axis inertia (Iy)	$kg.m^2$	$6.228e^{-3}$
7	z-axis inertia (Iz)	$kg.m^2$	$1.121e^{-2}$

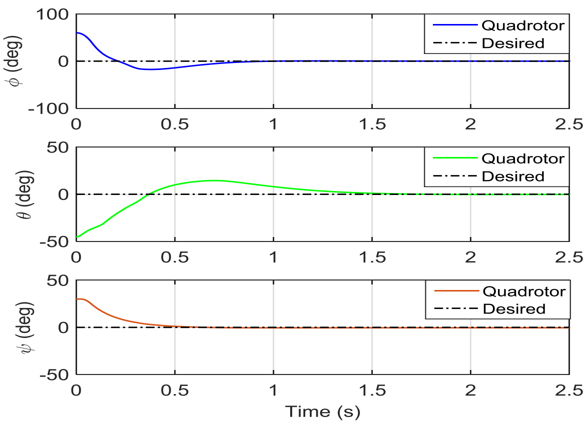

Figure 13. The history of the roll, pitch, and yaw angles of the quadrotor along with their reference values with the initial point described in Equation (15)

Figure 14 demonstrates the variations in the rotational velocities of rotors. As can be seen from Figures 13 and 14, the proposed controller achieved all expected aims.

Following, the performance of the proposed control algorithm will be evaluated in terms of path tracking.

7. 2. Simulation Results in Terms of Quadrotor Path Tracking

In this section, a three-dimensional spiral path flight with opening radius has been considered for the quadrotor. In order to travel the desired path, the trajectory values defined by Equations (16) to (19) were sent to the controller as inputs, and its performance was investigated in terms of tracking the reference inputs.

$$X_d = 0.5 * t * \sin(0.1 * t) \quad (16)$$

$$Y_d = 0.5 * t * \cos(0.1 * t) \quad (17)$$

$$Z_d = 0.4 * t \quad (18)$$

$$\psi_d = 40 * pi/180 * sin(0.2 * t) \quad (19)$$

In the previous step, the simulation results obtained for attitude control have been presented and discussed. In this section, simulation results on path tracking will be presented. Although there are different algorithms for path tracking purpose, each of which has its own advantageous and disadvantageous. These algorithms include optimal control, fuzzy algorithms, sliding mode algorithms, back stepping algorithms, Linear Quadratic Regulator (LQR) algorithms, etc. [21–23]. In this study, a non-linear PID controller based on recurrent neural network was designed and implemented for station keeping and path tracking of a quadrotor in the presence of different kinds of uncertainties. One of the advantageous of a recurrent neural network based non-linear PID controller is its capability to update control coefficients. In the case where a conventional PID

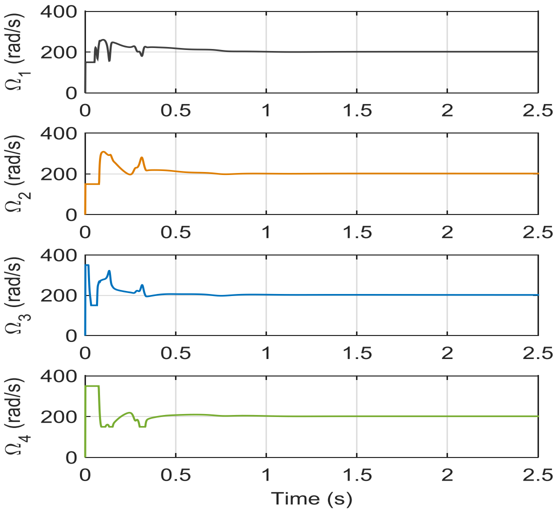

Figure 14. The angular velocity of the rotors

controller is used, the coefficients will not be updated effectively, which in turn, makes controllers unable to provide appropriate control commands. Nevertheless, if the control coefficients are adjusted properly, the mission will be performed without any serious problem, but the deviation of path tracking will be high. Figures 15 to 20 present the results obtained from both linear and non-linear intelligent PID controllers. As can be seen from these figures, although both controllers lead to acceptable results regarding path tracking, the deviation is smaller when using the non-linear intelligent PID controller. This is of great importance, especially in the case where external perturbations present. In such a case, the non-linear intelligent PID controller, due to updating control coefficient, shows better performance.

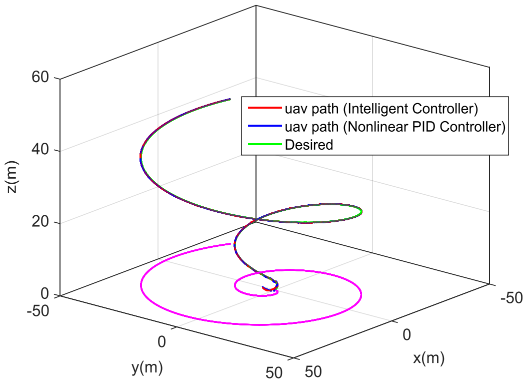

Figure 15. The three-dimensional representation of the path tracked over time

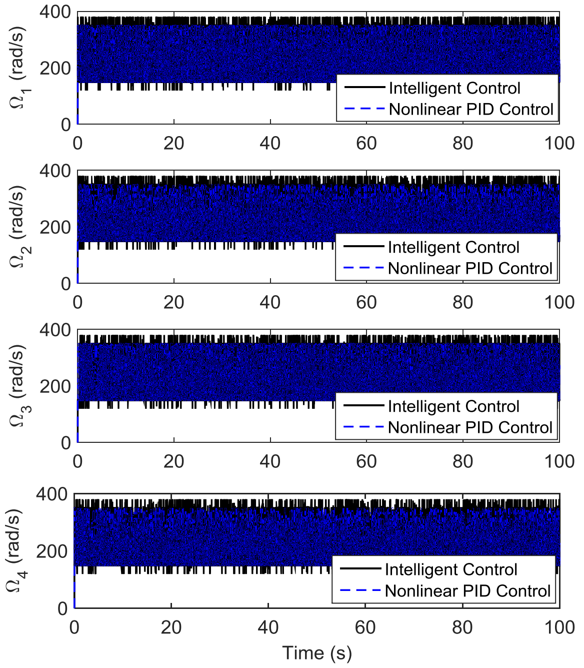

Figure 16. The angular velocity of each rotor of quadrotor obtained by smart control algorithm proposed in this study

In Figure 15, a three-dimensional plots of the desired trajectory and the path traveled by the quadrotor and also their projections onto the xy-plane are shown.

The simulation results in Figure 15 shows that the proposed controller can make the quadrotor tracks the desired trajectory. Towards a better understanding of the problem, following the motor rpms and path tracking errors will be presented. Figure 16 shows the time dependency of the angular velocity of each rotor adopted according to the control command given by the proposed algorithm, i.e. Equations (16) to (19).

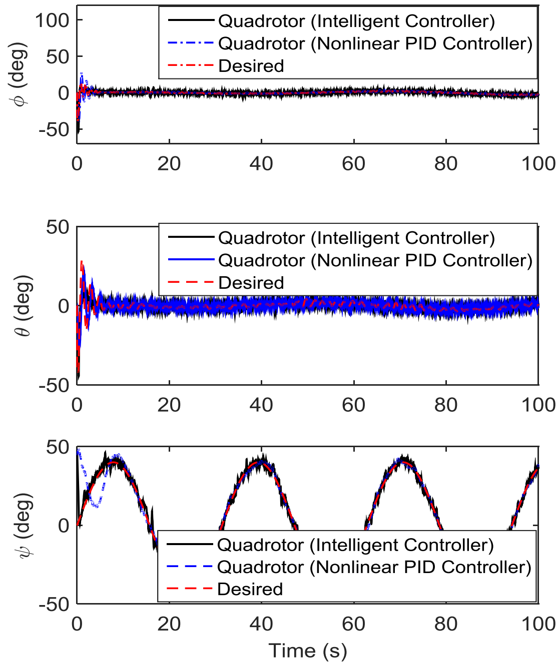

Figure 17. The history of the roll, pitch, and yaw angles of the quadrotor along with their reference values

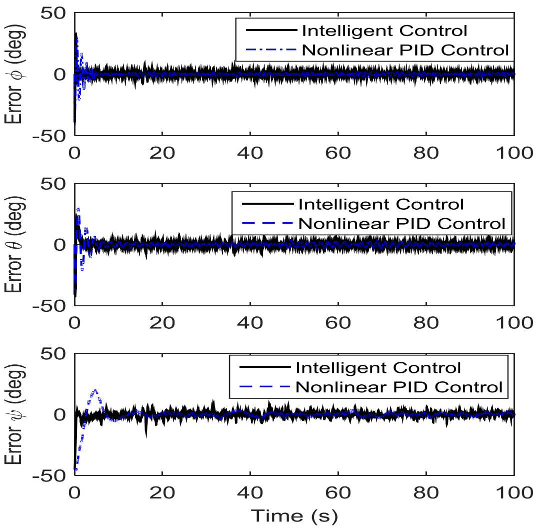

Figure 18. The deviations in the roll, pitch, and yaw angles with respect to the reference values of these angles

Following, time history of state variables of the quadrotor (angles and station) along with their desired value will be presented. Figure 17 shows the variations of the roll, pitch, and yaw angles along with their reference values. The desired values of the quadrotor station can be obtained from Equations (16) to (18). Moreover, it should be noted that the desired roll, pitch, and yaw angles are obtained from Equations (9), (10), and (19), respectively.

Figure 18 shows the deviations in the roll, pitch, and yaw angles with respect to the reference values of these angles.

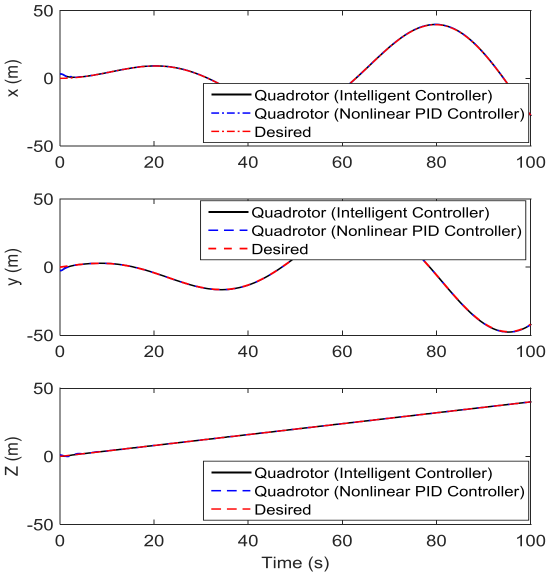

Figure 19. The history of longitude, latitude, and altitude variables of the quadrotor along with their reference values

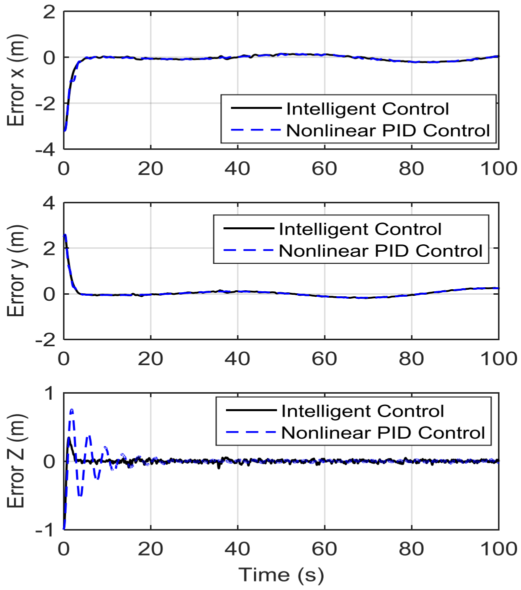

Figure 20. The deviations of longitude, latitude, and altitude positions of the quadrotor from their reference values

Figure 19 shows the time history of longitude, latitude, and altitude variables of the quadrotor along with their reference values. Figure 20 shows the deviations of longitude, latitude, and altitude positions of the quadrotor from their reference values.

According to the results presented above, it can be concluded that the proposed algorithm makes the quadrotor tracks the desired trajectory and stabilizes its attitude as well.

8. CONCLUSIONS

A neural network based station-keeping and tracking controller was designed and implemented. Firstly, we provided a brief introduction to the unmanned aerial vehicles and VTOLs. Then, a number of the control methods applied on quadrotors were reviewed. Sections 3 and 4 were devoted to describe the appropriate equations and models analyzing the behavior of the system and design the controller, respectively. In Sections 4, 5, and 6 control algorithm, neural networks, and the design of the nonlinear intelligent PID controller were discussed, respectively. In Section 7, the results of the simulation performed were presented in terms of station keeping and path tracking. The performance of the proposed algorithm was also investigated. It was shown that the proposed algorithm successfully makes the quadrotor tracks the desired trajectory and stabilizes its attitude as well.

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Design of an Intelligent Controller for Station Keeping, Attitude Control, and Path Tracking of a Quadrotor Using Recursive Neural Networks

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P A P E R I N F O

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چکیده

در سال‌های اخیر تمایل فزاینده‌ای برای بهره‌برداری از وسایل پرنده بدون سرنشین و پژوهش پیرامون آن‌ها پدید آمده است. در همین راستا، حفظ موقعیت، حفظ وضعیت و تعقیب مسیر این دسته از پرنده‌ها نیز اهمیت فراوانی پیدا کرده است. دلیل این مسئله آن است که برهم‌کنش میان جریان‌های اغتشاشی نیروهای آیرودینامیکی پیچیده‌ای را به سامانه اعمال می‌کنند. به جهت آن که دینامیک یک کوادروتور غیرخطی بوده و سامانه از نوع چندمتغیره می‌باشد، مضاف بر آن سامانه دارای شش درجه‌ی آزادی برای تنها چهار ورودی کنترلی است، بنابراین می‌توان آن را یک سامانه‌ی زیرتحریک در نظر گرفت. به همین دلیل است که در مورد کوادروتورها نمی‌توان از الگوریتم‌های متداول مورد استفاده برای تعقیب مسیر پرنده‌های بدون سرنشین دیگر بهره برد. گام اساسی در ساخت یک پرنده‌ی بدون سرنشین کاملاً خودکار، طراحی یک کنترلر برای پایدارسازی آن در حضور اغتشاشات محیطی و عدم قطعیت‌ها و نیز راهبری در یک مسیر مشخص است. هدف این پژوهش، طراحی و اجرای یک کنترلر هوشمند برای حفظ موقعیت، کنترل وضعیت و تعقیب مسیر یک کوادروتور است. در این پژوهش، برای نیل به این هدف از روش شبکه‌ی هوش مصنوعی استفاده شد. این روش یکی از ابزارهای بسیار کارآ و مفید در بهینه‌سازی یک سامانه‌ی کنترلی است. در این مقاله، ابتدا روش‌های کنترلی متداول که بر کوادروتورها اعمال می‌شود، مرور شده است. در ادامه، به‌منظور تحلیل رفتار سامانه و نیز طراحی کنترلر، معادلات حالت یک کوادروتور ارائه و مورد بحث قرار گرفته است. سپس، نحوه‌ی طراحی الگوریتم کنترلی PID غیرخطی مبتنی بر شبکه‌ی هوش مصنوعی بازگشتی ارائه می‌شود. درنهایت، نتایج شبیه‌سازی‌های صورت‌گرفته ارائه و بر اساس این نتایج، عملکرد الگوریتم پیشنهادی بررسی می‌شود. نتایج شبیه‌سازی نشان می‌دهد که با استفاده از الگوریتم پیشنهادی، هر دو هدف حفظ وضعیت و تعقیب مسیر مطلوب توسط کوادروتور تامین می‌شود.

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