https://doi.org/10.1590/jatm.v15.1303

ORIGINAL PAPER

Position and Attitude Control Based on Single Neuron PID With Gravity Compensation for Quad Rotor UAV

Haitao Zhang[1,*], Lulu Yang[1]

1.Henan University of Science and Technology – College of Information Engineering – Automation Department – Luoyang/ Henan – China.

*Correspondence author: zhang_haitao@163.com

ABSTRACT

Aimed at the deficiency of existing PID controller for quad rotor UAV, a single neuron PID controller with gravity compensation is presented. After using feed forward control to compensate gravity, the position loop adopts PID control to ensure control accuracy, while the attitude loop adopts single neuron control to increase adaptive ability. Then, by using Matlab/simulink simulation software, the position control of quad rotor UAV is carried out, and the simulation result shows, compared with the traditional double closed loop PID controller, the control algorithm based on the Single Neuron adaptive PID with gravity compensation can effectively improve the robustness and adaptability of the quad rotor UAV system.

Keywords: Quad rotor UAV system; Double closed loop; Single neuron; Gravity compensation.

INTRODUCTION

Compared with the traditional helicopter, the quad rotor UAV has many advantages. It has the characteristics of simpler structure, smaller volume and more stable flight, which makes it more practical in various environments (Shi *et al.* 2020). In recent years, the quad rotor UAV has been widely used in military, remote sensing, surveying, mapping, and many other fields (Guan *et al.* 2021; Gu *et al.* 2021). Because the quad rotor UAV has the characteristics of strong coupling, nonlinearity and under actuation, the control method has been one of main research directions. At present, many control methods, such as PID control (Miranda-Colorado and Aguilar 2020; Rosales *et al.* 2018), sliding mode control (Mofid and Mobayen 2018; Oba *et al.* 2018; Zhang *et al.* 2021), intelligent control (Guan *et al.* 2021), backstepping control (Zhou *et al.* 2018), L1 Adaptive control (Souanef 2023), fault tolerant control (Di *et al.* 2023), and robust control (Weng *et al.* 2022; Yang 2021) have been applied to the control of quad rotor UAV. Though the traditional PID controller is easily used to implement the control of the quad rotor UAV, the fixed PID parameters cannot adapt to the changes of external conditions and control object parameters, which makes it difficult to achieve the desired control effect. However, single neuron PID method has been applied to some control systems and has achieved good control results (Feng 2022; Yanjun *et al.* 2018; Zhong *et al.* 2020). Single neuron has a strong self-learning ability, and its nonlinear

Received: Jan 25, 2023 | **Accepted:** May 14, 2023
Section editor: Othon Winter
Peer Review History: Single Blind Peer Review.

mapping function can solve the nonlinear problems. Compared with the traditional PID control algorithm, the single neuron PID method needs to calculate the PID parameters in real time, but can obtain better performance.

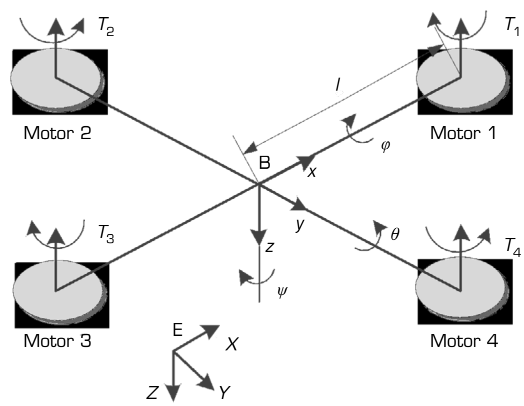
Therefore, in order to achieve a better control effect, we study the design of variable parameter controller based on a single neuron, so that the three parameters of PID controller based on this algorithm can be adjusted online, and the adaptive control of quad rotor UAV is realized. In addition, in height control, gravity becomes a constant disturbance, which is prone to overshoot and even instability. Therefore, we use feed forward control to counteract the influence of gravity in height control. The simulation results show that the PID controller based on S-function RBF neural network has good stability and adaptability.

MODELING OF QUAD ROTOR UAV

Flight principle of quad rotor UAV

The quad rotor UAV is a rigid body with six spatial degrees of freedom, including three translational motions of longitudinal, transverse and altitude, and three rotational motions of roll, pitch and yaw. The quad rotor UAV has only four inputs, which makes it an underactuated system.

The airframe structure of quad rotor UAV is usually cross-shaped or X-shaped. The difference between the two forms lies in the choice of nose direction. The X-shaped body structure is easy to operate, while the cross-shaped is easy to use and control. In the paper we study the cross-shaped quad rotor UAV which is shown in Fig. 1 (Mian and Dao-bo Wang 2008).



Source: Retrieved from Mian (2008, p.540).

Figure 1. Structure of quad rotor UAV.

In Fig. 1, the four motors can be divided into two pairs. Motor 1 and Motor 3 are one pair, and Motor 2 and Motor 4 are the other pair. The motor pair (1, 3) is a clockwise positive propeller and the motor pair (2, 4) is a counterclockwise negative propeller.

The quad rotor UAV mainly includes the following motion forms: hover, vertical take-off and landing, roll, pitch, and yaw. When the speed of the four rotors changes by the same amount, the lift force will change. If the lift is equal to gravity, the UAV is in hovering state; if the lift is greater than gravity, the UAV will move upward; otherwise, the UAV will move downward.

When the speed of the motor pair (2, 4) remains unchanged, the pitch motion can be obtained by increasing (or decreasing) the speed of Motor 1 and decreasing (or increasing) the speed of Motor 3. When the speed of the motor pair (1, 3) remains unchanged, the roll motion can be obtained by increasing (or decreasing) the speed of Motor 2 and decreasing (or increasing) the speed of Motor 4. The yaw motion can be obtained by increasing (or decreasing) the speed of the motor pair (1, 3) and decreasing (or increasing) the speed of the motor pair (2, 4) (Gong *et al.* 2012).

Whether the motor speed increases or decreases depends on the direction of pitch, roll or yaw motion. The UAV can adjust the motor speed to control the required attitude for flight.

Dynamic model of the quad rotor UAV

In Fig. 1, l represents the distance of the motor from the pivot center. The center of gravity of the UAV is also the origin of the body fixed frame. The origin of the earth fixed frame is the take-off point of the UAV. The earth fixed frame and the body fixed frame are represented by E = {X, Y, Z} and B = {x, y, z}, respectively.

Three attitude angles of the quad rotor UAV are roll angleφ, pitch angle θ and yaw angle ψ, respectively. φ, θ and ψ represent Euler angles about x, y, z body axes, respectively. T_n (n=1, 2, 3, 4) represents the thrust force produced by each propeller. W_n (n=1, 2, 3, 4) represents the speed of the four rotors.

In practice, the flight situation of the quad rotor UAV is very complicated. In order to simplify the mathematical model of the quad rotor UAV, the following conditions are assumed.

- UAV is a rigid body.
- The mass of UAV remains unchanged under all flight status.
- The center of the UAV coincides with the origin of the body fixed frame.

In the body fixed frame, $[x, y, z]^T$ represents the position state of UAV, and $[\varphi, \theta, \psi]^T$ represents the attitude angle of UAV. The angle range of φ and θ is $(-\pi/2, \pi/2)$, and the angle range of ψ is $(-\pi, \pi)$.

The transformation relationship between the two frames can be obtained by first rotating the roll angle of the body fixed frame with respect to the OX axis, then rotating the pitch angle of the body fixed frame with respect to the OY axis, and finally rotating the yaw angle of the body fixed frame with respect to the OZ axis. The transformation matrix between two frames is (Eq. 1):

$$ {}_B^E R = {}_E^B R^T = \begin{bmatrix} c\theta c\psi & -c\varphi s\psi + s\varphi s\theta c\psi & s\varphi s\psi + c\varphi s\theta c\psi \\ c\theta s\psi & c\varphi c\psi + s\varphi s\theta c\psi & -s\varphi c\psi + c\varphi s\theta s\psi \\ -s\theta & c\theta s\varphi & c\theta c\varphi \end{bmatrix} \tag{1} $$

where $s\varphi$, $s\theta$, $s\psi$, $c\varphi$, $c\theta$ and $c\psi$ are the simplified expression for $\sin\varphi$, $\sin\theta$, $\sin\psi$, $\cos\varphi$, $\cos\theta$ and $\cos\psi$.

The control inputs to quad rotor includes vertical force u_1, roll moment u_2, pitch moment u_3 and yaw moment u_4, which are defined as Eq. 2:

$$ \begin{cases} u_1 = -\left(T_1 + T_2 + T_3 + T_4\right) = -K_T \sum_{i=1}^{4} w_i^2 \\ u_2 = T_2 - T_4 = K_T l\left(w_2^2 - w_4^2\right) \\ u_3 = T_1 - T_3 = K_T l\left(w_1^2 - w_3^2\right) \\ u_4 = T_2 + T_4 - T_1 - T_3 = K_D\left(w_2^2 + w_4^2 - w_1^2 - w_3^2\right) \end{cases} \tag{2} $$

By arranging Eq. 2, we can get Eq. 3:

$$ \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} -K_T & -K_T & -K_T & -K_T \\ 0 & K_T l & 0 & -K_T l \\ K_T l & 0 & -K_T l & 0 \\ -K_D & K_D & -K_D & K_D \end{bmatrix} \begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{bmatrix} = A \begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{bmatrix} \tag{3} $$

where K_T and K_D are constants dependent on air density and UAV parameters.

From Eq. 2, we can get Eq. 4

$$\begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{bmatrix} = A^{-1} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \tag{4}$$

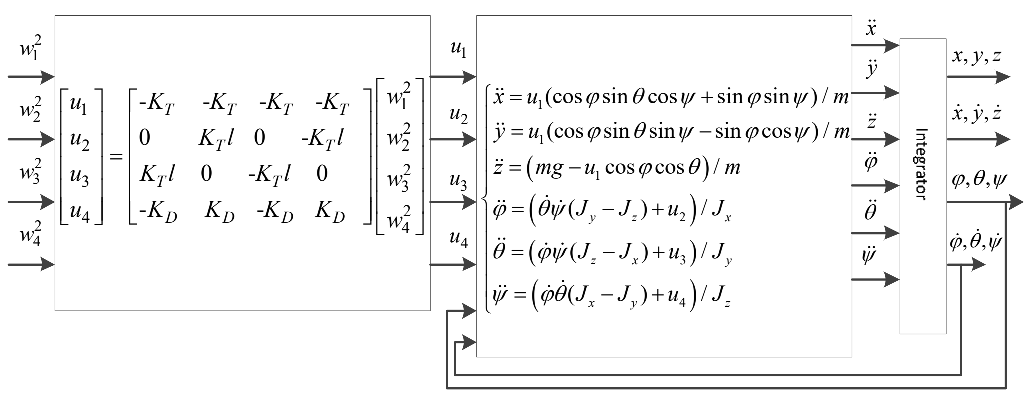
In the body fixed frame, the lift force F_B received by the four rotors can be expressed as $F_B = [0\ 0\ u_1]^T$.
Using the frame transformation matrix R_B^E, the lift force F_E in the earth fixed frame can be obtained as (Eq. 5):

$$\begin{cases} \ddot{x} = \dfrac{u_1(\cos\varphi \sin\theta \cos\psi + \sin\varphi \sin\psi)}{m} \\ \ddot{y} = \dfrac{u_1(\cos\varphi \sin\theta \sin\psi - \sin\varphi \cos\psi)}{m} \\ \ddot{z} = \dfrac{mg - u_1 \cos\varphi \cos\theta}{m} \end{cases} \tag{5}$$

Let J_x, J_y and J_z be the moment of inertia for the x, y, and z axes of quad rotor UAV. Assuming that quad rotor UAV is completely symmetrical in structure, ignoring the air resistance and gyro effect, we can get the following conclusions when the quad rotor moves at a small angle (Eq. 6).

$$\begin{cases} \ddot{\varphi} = \dfrac{\dot{\theta}\dot{\psi}(J_y - J_z)}{J_x} + \dfrac{u_2}{J_x} \\ \ddot{\theta} = \dfrac{\dot{\varphi}\dot{\psi}(J_z - J_x)}{J_y} + \dfrac{u_3}{Jy} \\ \ddot{\psi} = \dfrac{\dot{\varphi}\dot{\theta}(J_x - J_y)}{J_z} + \dfrac{u_4}{J_z} \end{cases} \tag{6}$$

Finally, the schematic diagram of the quad rotor UAV model is shown as Fig. 2.



Source: Elaborated by the authors.

Figure 2. Schematic diagram of the quad rotor UAV model.

The design of control algorithm

The control of the quad rotor UAV is achieved by adjusting the speed of the four rotors. Generally, the four rotors are controlled by double loops. One is the inner ring, which is used to control the attitude of the four rotors; one is the outer ring, which is used to control the position of the four rotors. Specific control methods will be introduced below.

Height Control based on Gravity compensation let $[x_c\ y_c\ z_c]^T$ the given position, and $[x, y, z]^T$ be the feedback position, then the deviation vector $[e_x\ e_y\ e_z]$ is obtained as follows (Eq. 7):

$$\begin{cases} e_x(k) = x_c(k) - x(k) \\ e_y(k) = y_c(k) - y(k) \\ e_z(k) = z_c(k) - z(k) \end{cases} \tag{7}$$

Height control adopts PD control (Eq. 8):

$$U_{z1} = U_z + u_{z0} = k_{pz}e_z + k_{dz}\dot{e}_z + u_{z0} \tag{8}$$

where k_{pz} and k_{dz} are proportional and differential coefficients respectively.

The control quantity U_z is used to determine the acceleration of the quad rotor UAV. When the quad rotor UAV hovers in the air, the gravity will be equal to the lift force. Therefore, we can use feed forward control to counteract the effect of gravity.

u_{z0} is used to counteract the gravitational acceleration of the quad rotor UAV. So we get Eq. 9:

$$u_{z0} = g \tag{9}$$

After the feed forward control is used to counteract the gravity, the gain k_{pz} in the height control algorithm will be reduced, which is conducive to the system stability.

Position control in horizontal plane

We construct the following controller in the horizontal plane (Eq. 10):

$$\begin{cases} U_x = k_{px}e_x + k_{ix}\int e_x dt + k_{dx}\dot{e}_x + \ddot{x}_c \\ U_y = k_{py}e_y + k_{iy}\int e_y dt + k_{dy}\dot{e}_x + \ddot{y}_c \end{cases} \tag{10}$$

where k_{px} , k_{iy} and k_{dx} are proportional, integral and differential coefficients of x-direction controller U_x respectively, k_{py}, k_{iy} and k_{dy} are proportional, integral and differential coefficients of y-direction controller U_y respectively.

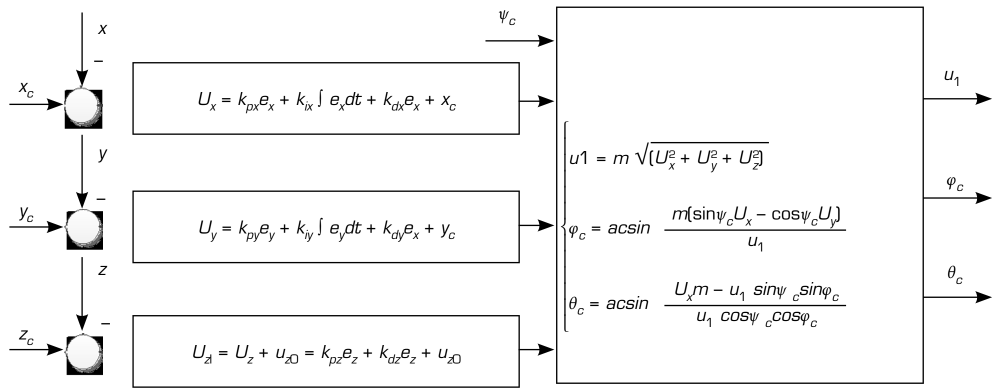
The control quantity U_x and U_y determines the accelerations in the x and y direction.

The Eq. 11 can be obtained utilizing Eqs. 5, 8 and 9.

$$\begin{cases} u_1 = m\left(g + U_z\right) / cos\theta cos\varphi \\ \varphi_c = acsin\dfrac{m\left(\sin\psi_c U_x - \cos\psi_c U_y\right)}{u_1} \\ \theta_c = arctan\dfrac{U_x m - u_1 sin\psi_c sin\varphi_c}{u_1 cos\psi_c cos\varphi_c} \end{cases} \tag{11}$$

In Eq. 11, φ_c and θ_c can be taken as the given values of roll angle and pitch angle in the attitude loop. The schematic diagram of position control loop is shown as Fig. 3.

Next, we will design the attitude loop controller.



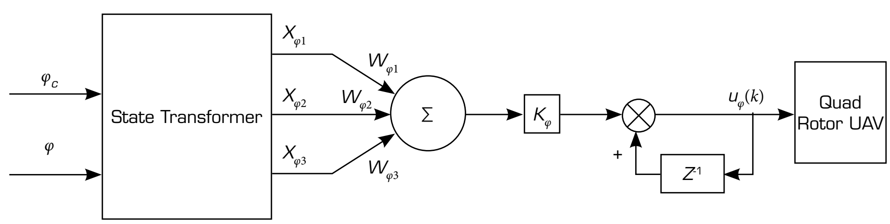
Source: Elaborated by the authors.

Figure 3. Schematic diagram of position control loop.

Single Neuron adaptive PID attitude controller

As the basic unit of neural networks, the neuron has the self-learning ability and adaptability. Single neuron adaptive PID algorithm is easy to realize, and has better robustness. Besides, the algorithm does not need an accurate mathematical model of the controlled object (Wang *et al.* 2021). Therefore, the design of single neuron adaptive PID controller does not need system modeling. Considering these characteristics of single neuron control algorithm, we introduce the single neuron adaptive PID control algorithm into the control of three attitude angles in the attitude loop.

The roll, pitch and yaw angle control methods using single neuron adaptive PID controller are the same. Figure 4 is the model structure of single neuron adaptive PID controller for roll angle.



Source: Elaborated by the authors.

Figure 4. Structure of single neuron adaptive PID.

In Fig. 4, φ_c and φ are respectively the given and output of roll angle, and the deviation meets $e_\varphi(k) = \varphi_c(k) - \varphi(k)$. The control quantity $u_\varphi(k)$ is generated through the single neuron associated with the search and self-learning (Hu *et al.* 2015). $x_{\varphi1}$,$x_{\varphi2}$ and $x_{\varphi3}$ are the inputs of the single neuron, which meet the Eq. 12:

$$\begin{cases} x_{\varphi1}(k) = e_\varphi(k) - e_\varphi(k-1) \\ x_{\varphi2}(k) = e_\varphi(k) \\ x_{\varphi3}(k) = e_\varphi(k) - 2e_\varphi(k-1) + e_\varphi(k-2) \end{cases} \tag{12}$$

$w_{\varphi1}$, $w_{\varphi2}$ and $w_{\varphi3}$ are respectively the weight value of the input $x_{\varphi1}$, $x_{\varphi2}$ and $x_{\varphi3}$.
K_φ is the proportional coefficient of the neuron, and $K_\varphi > 0$, then the output of the single neuron controller can be expressed at Eq. 13:

$$u_\varphi(k) = u_\varphi(k-1) + K_\varphi \sum_{i=1}^{3} w_{\varphi i}(k) x_{\varphi i}(k) \tag{13}$$

In the single neuron controller, the coefficient K_φ reflects the adjusting amplitude. Generally, if the deviation is bigger, the adjusting amplitude is also bigger to meet the requirement of system rapidity; if the deviation is smaller, the adjusting amplitude is also smaller to meet the requirement of system stability of the system. The coefficient K_φ is usually a function of the deviation e_φ, and their relationship is as follows (Eq. 14):

$$K_\varphi = \mu_\varphi \left| e_\varphi(k) \right|^{\alpha_\varphi} \tag{14}$$

where $\alpha_\varphi < 1$, and μ_φ is constant. Usually, if μ_φ is bigger, the system rapidity is better, but the system overshoot becomes larger. If α_φ is smaller, the system stability is better (Wang *et al.* 2021).

The single neuron PID control method implements the adapting control of system by adjusting the weight coefficient. We use Supervised Hebb learning rules as the learning method of weight value. In order to ensure the convergence and robustness of learning method, we normalize the Eq. 13, and get the following the expression (Eq. 15–17):

$$u_\varphi(k) = u_\varphi(k-1) + K_\varphi \sum_{i=1}^{3} w_{\varphi i}{}'(k) x_{\varphi i}(k) \tag{15}$$

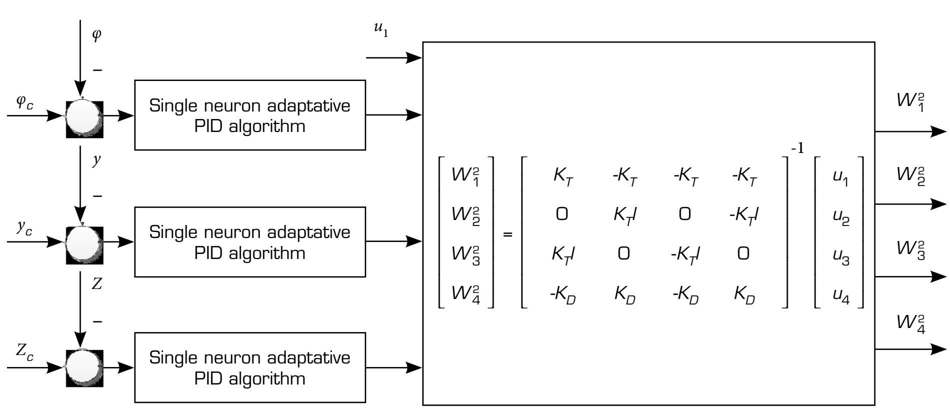
$$w_{\varphi i}{}'(k) = w_{\varphi i}(k) / \sum_{i=1}^{3} \| w_{\varphi i}(k) \| \tag{16}$$

$$\begin{cases} w_{\varphi 1}(k+1) = w_{\varphi 1}(k) + \eta_{\varphi P} e_\varphi(k) x_{\varphi 1}(k) \\ w_{\varphi 2}(k+1) = w_{\varphi 2}(k) + \eta_{\varphi I} e_\varphi(k) x_{\varphi 2}(k) \\ w_{\varphi 3}(k+1) = w_{\varphi 3}(k) + \eta_{\varphi D} e_\varphi(k) x_{\varphi 3}(k) \end{cases} \tag{17}$$

where $\eta_{\varphi P}$, $\eta_{\varphi I}$ and $\eta_{\varphi D}$ proportional, integral and differential coefficients respectively for the roll angle.

Similar to the control of roll angle, we can use the single neuron control algorithm to obtain the control quantity u_θ of pitch angle and the control quantity u_ψ of yaw angle. So we get roll moment $u_2 = u_\varphi$, pitch moment $u_3 = u_\theta$ and yaw moment input $u_4 = u_\psi$.

The schematic diagram of attitude control loop is shown as Fig. 5.



Source: Elaborated by the authors.

Figure 5. Schematic diagram of attitude control loop.

The single neuron adaptive PID control with gravity compensation

Combining the position loop with the attitude loop, a single neuron adaptive PID controller with gravity compensation for a quad rotor UAV is obtained.

The single neuron adaptive PID controller improves the traditional PID controller, and overcomes the sensitivity to parameter change of the controlled object in the control system. The dynamic model parameters of quadrotor UAV change with the change of attitude, and single neuron PID can adapt to the change of model parameters by changing PID parameters. It has better learning ability and easily ensures real-time performance (Hu *et al.* 2015). Therefore, the quad rotor UAV can get better control effect under the single neuron adaptive PID controller with gravity compensation.

SIMULATION RESULTS

In order to prove the effectiveness of the proposed method, a quad rotor UAV is taken as the controlled object for simulation in Matlab/simulink environment.

In the simulation, it is assumed that the flight environment is calm, and there is no significant disturbance of atmospheric flow, ignoring the influence of air resistance.

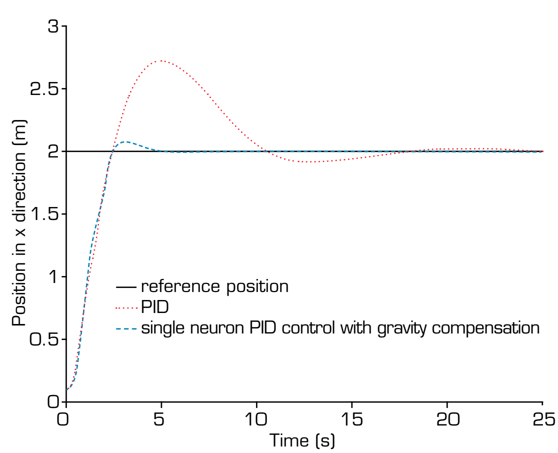
The system parameters of a quad rotor UAV is summarized as follows:

- Distance of the motor from the pivot center (l) is 0.3 m.
- Mass moments of the airframe inertia J_x, J_y and J_z along the x, y and z axe is 0.0154 kg·m², 0.0150 kg·m² and 0.0309 kg·m² respectively.
- Total mass of the airframe (m) is 0.6 kg.

Let us simulate the closed loop system with nonlinear control algorithm. The initial conditions used are $\varphi = \theta = \psi = 0, x = y = 0$ and z=-1 m. The reference inputs to the controller are $x_c = 2m$, $y_c = 2m$, $z_c = 2m$ and $\psi_c = 2rad$.

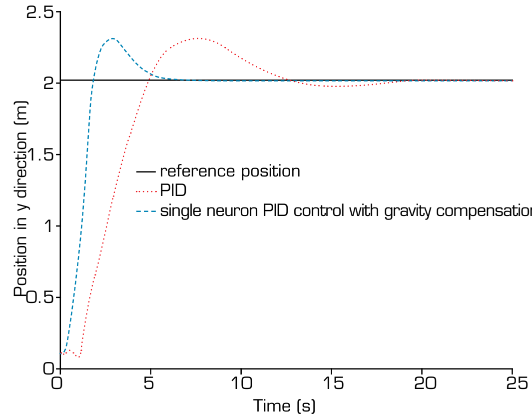
Using PID method, and single neuron adaptive PID with gravity compensation, the step responses are observed. Figures 6–9 show the response curve of the proposed control algorithm.

The single neuron adaptive PID with gravity compensation possesses high control accuracy, small overshoot and short adjusting time compared with the traditional PID methods. It can be seen that the single neuron adaptive PID realizes the automatic adjustment of control parameters, and the feed forward control realizes the gravity compensation, so the performance of the whole control system is improved. Therefore, the control method based on single neuron adaptive PID with gravity compensation is able to effectively meet the control requirements of the quad rotor UAV.



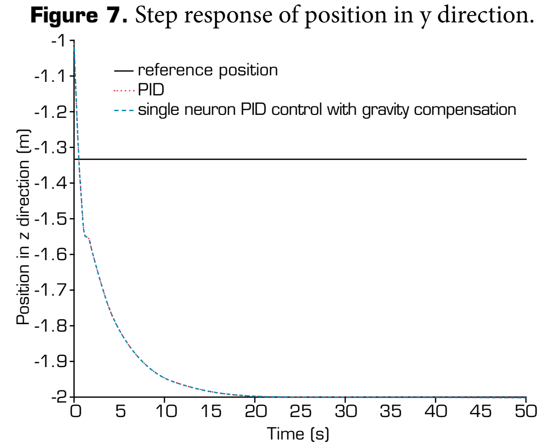
Source: Elaborated by the authors.

Figure 6. Step response of position in x direction.



Source: Elaborated by the authors.

Figure 7. Step response of position in y direction.



Source: Elaborated by the authors.

Figure 8. Step response of position in z direction.

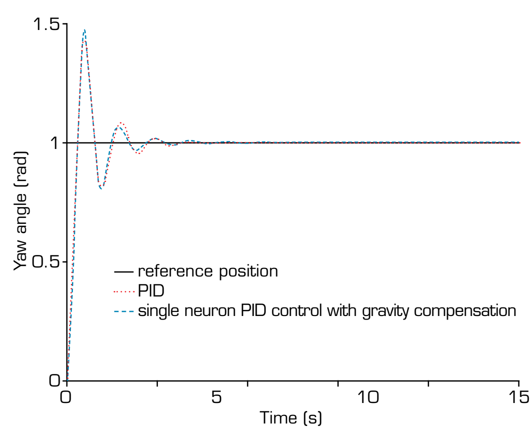


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Figure 9. Step response of yaw angle.

CONCLUSION

The paper is set out to study the position and attitude control of quad rotor UAV. The control algorithm of single neuron adaptive PID with gravity compensation is proposed. The research has also shown that the proposed method possesses more stable output, short adjustment time and strong robustness, and can meet the requirements of the quad rotor UAV. The major limitation of this study is that it does not consider the influence of some factors, such as air resistance, wind resistance, and gyroscopic effect, and the future research should carefully consider the effects.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Zhang H; **Data curation:** Zhang H and Yang L; **Acquisition of funding:** Zhang H; **Research:** Zhang H and Yang L; **Methodology:** Zhang H and Yang L; **Project administration:** Zhang H and Yang L; **Resources:** Zhang H; **Supervision:** Zhang H and Yang L; **Validation:** Zhang H and Yang L; **Writing - Preparation of original draft:** Zhang H and Yang L; **Writing – Proofreading and editing:** Zhang H.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

FUNDING

Not applicable.

ACKNOWLEDGEMENTS

Not applicable.

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