Nonlinear Intelligent Flight Control for Quadrotor Unmanned Helicopter

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Abstract: Quadrotor unmanned helicopter is a new popular research platform for unmanned aerial vehicle (UAV), thanks to its simple construction, vertical take-off and landing (VTOL) capability. Here a nonlinear intelligent flight control system is developed for quadrotor unmanned helicopter, including trajectory control loop composed of co-controller and state estimator, and attitude control loop composed of brain emotional learning (BEL) intelligent controller. BEL intelligent controller based on mammalian middle brain is characterized as self-learning capability, model-free and robustness. Simulation results of a small quadrotor unmanned helicopter show that the BEL intelligent controller-based flight control system has faster dynamical responses with higher precision than the traditional controller-based system.

Key words: quadrotor unmanned helicopter; flight control; brain emotional learning (BEL); intelligent control

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0 Introduction

Quadrotor unmanned helicopter is an emerging rotorcraft concept for unmanned aerial vehicle (UAV). This type of aircraft consists of four rotors with two pairs of counter-rotating, fixed-pitch blades located at the four corners. Thanks to its specific capabilities in surveillance, search and rescue, the quadrotor unmanned helicopter is widely researched by scholars and engineers. However, trajectory control with high performance of quadrotor unmanned helicopter was indispensable for real applications. A direct approximate-adaptive control using cerebellar model articulation controller (CMAC) nonlinear approximators for an experimental prototype quadrotor unmanned helicopter is investigated in Ref. [1]. A quaternion-based feedback that considered a priori input bounds was developed and experimentally applied to the attitude stabilization of a quadrotor mini-helicopter[2]. Moreover, a switching model predictive attitude controller based on a piecewise affine model of the attitude dynamics was designed, and verified by experiments in the execution of sudden maneuvers subject to forcible wind disturbances[3].

Recent researches have verified the importance of emotion in animal behavior and even human decision-making process. Therefore, modeling of the emotional learning process attracts many researchers. Some of them focus on internal representation of emotional learning to formalize the brain reaction to emotional stimuli. In Ref. [4], a computational model of amygdala and context-processing was presented, called the brain emotional learning (BEL) model. BEL model learns to react to new stimuli on a basis of generating reward signals. Amygdala learns to associate between emotionally charged and neu-

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tral stimuli, while the orbitofrontal cortex inhabits inappropriate experience and learning connection. As a biological computing system, BEL model can be conceptualized as a new type of artificial neural network, and it is also parallel and distributed. BEL model has been utilized for controlling several real systems. Based on the cognitively motivated open loop model, a BEL-based intelligent controller was originally introduced in Ref. [5], and was utilized in several real system control applications, such as electrically heated micro-heat exchanger plant[6], washing machine[7], laboratorial overhead crane[8], and flight simulation turntables[9-10]. Moreover, the obtained embedded and model-free controller can be applied to other systems with different platforms, and the reusability and extendibility of models are considered in different models.

Here, the BEL model is initially used for attitude control of a quadrotor helicopter, and is associated with a nonlinear controller to control the flight trajectory. The purpose is to develop a reliable intelligent controller with higher performance.

1 Model Descriptions of Quadrotor and BEL

1.1 Quadrotor helicopter model

The quadrotor unmanned helicopter is a complex mechanical system that collects numerous physical effects from mechanics and aerodynamics domains. The structure of quadrotor is supposed to be rigid and symmetrical. Based on the system modeling method in Ref. [11], a nonlinear model of the quadrotor unmanned helicopter is given in the following. The rotation of quadrotor unmanned helicopter in space can be parameterized using Euler angles, quaternions and Tait-Bryan angles. The axes are directed as for a craft moving in the positive x direction, with the right side corresponding to the positive y direction, and the vertical underside corresponding to the positive z direction. Considering a right-hand oriented coordinate system, there are three angles (θ,ϕ,ψ) individually called pitch, roll and yaw. The body angular rates (p, q, r) are physically measured with gyroscopes.

The dynamic model is derived using Euler-Lagrange formalism. If applying small angle approximation, the dynamics of the rotation subsystem becomes

$$\begin{cases}\ddot{\theta}=\dfrac{-J_{\mathrm{r}}\Omega_{\mathrm{r}}\dot{\phi}}{I_{yy}}+\dfrac{(I_{zz}-I_{xx})\dot{\psi}\dot{\phi}}{I_{yy}}+\dfrac{l(T_1-T_3)}{I_{yy}}+ \\ \qquad \dfrac{h\sum_{i=1}^{4}H_{xi}}{I_{yy}}+\dfrac{(-1)^{i+1}\sum_{i=1}^{4}R_{myi}}{I_{yy}}+\dfrac{C_zAP\dot{\theta}\,|\dot{\theta}|\,l^2}{4I_{yy}} \\ \ddot{\phi}=\dfrac{J_{\mathrm{r}}\Omega_{\mathrm{r}}\dot{\theta}}{I_{xx}}+\dfrac{(I_{yy}-I_{zz})\dot{\psi}\dot{\theta}}{I_{xx}}+\dfrac{l(T_4-T_2)}{I_{xx}}- \\ \qquad \dfrac{h\sum_{i=1}^{4}H_{yi}}{I_{xx}}+\dfrac{(-1)^{i+1}\sum_{i=1}^{4}R_{mxi}}{I_{xx}}+\dfrac{C_zAP\dot{\phi}\,|\dot{\phi}|\,l^2}{4I_{xx}} \\ \ddot{\psi}=\dfrac{J_{\mathrm{r}}\dot{\Omega}_{\mathrm{r}}}{I_{zz}}+\dfrac{(I_{xx}-I_{yy})\dot{\theta}\dot{\phi}}{I_{zz}}+\dfrac{(-1)^{i}\sum_{i=1}^{4}Q_i}{I_{zz}}+ \\ \qquad \dfrac{l(H_{x2}-H_{x4})}{I_{zz}}+\dfrac{l(H_{y3}-H_{y1})}{I_{zz}}\end{cases} \tag{1}$$

where $\Omega_{\mathrm{r}}=\Omega_1+\Omega_3-\Omega_2-\Omega_4$, $\Omega_{1,2,3,4}$ are the propeller angular rates. b is the thrust factor, d the drag factor, and J_{r} the rotor inertia. I_{xx}, I_{yy} and I_{zz} are the inertia moments. $(I_{yy}-I_{zz})\dot{\psi}\dot{\theta}$, $(I_{zz}-I_{xx})\dot{\psi}\dot{\phi}$ and $(I_{xx}-I_{yy})\dot{\theta}\dot{\phi}$ are the body gyro effects; $J_{\mathrm{r}}\dot{\theta}\Omega_{\mathrm{r}}$ and $J_{\mathrm{r}}\Omega\dot{\phi}$ are the propeller gyro effects, $l(-T_2+T_4)$ the roll actuator action; $h\sum_{i=1}^{4}H_{yi}$ and $h\sum_{i=1}^{4}H_{xi}$ the hub moments due to sideward flight and forward flight, respectively. $(-1)^{i+1}\sum_{i=1}^{4}R_{mxi}$ and $(-1)^{i+1}\sum_{i=1}^{4}R_{myi}$ are the rolling moments due to forward flight and sideward flight, respectively; $l(T_1-T_3)$ is the pitch actuators action, $J_{\mathrm{r}}\dot{\Omega}_{\mathrm{r}}$ the inertial counter-torque, $(-1)^{i}\sum_{i=1}^{4}Q_i$ the counter-torque unbalance, and $l(H_{x2}-H_{x4})$, $l(H_{y3}-H_{y1})$ the hub force unbalances in forward and sideward flights, respectively[11].

And then, the kinematics of the quadrotor helicopter can be expressed by

$$\begin{cases}\ddot{z}=g-\dfrac{\cos\psi\cos\phi\sum_{i=1}^{4}T_i}{m}\\ \ddot{x}=\dfrac{(\sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi)\sum_{i=1}^{4}T_i-\sum_{i=1}^{4}H_{xi}-0.5C_xA_c\rho\dot{x}\,|\dot{x}|}{m}\\ \ddot{y}=\dfrac{(\cos\psi\sin\phi+\sin\psi\sin\theta\cos\phi)\sum_{i=1}^{4}T_i-\sum_{i=1}^{4}H_{yi}-0.5C_yA_c\rho\dot{y}\,|\dot{y}|}{m}\end{cases} \tag{2}$$

where x, y, z are the positions in body coordinate frame, H the hub force, m the overall mass, A_c the fuselage area, T the thrust force, $\cos\psi\cos\phi\sum_{i=1}^{4}T_i$ the actuator action, $-\sum_{i=1}^{4}H_{xi}$ the hub force in the x axis, $0.5C_xA_c\rho\dot{x}\,|\dot{x}|$ and $0.5C_yA_c\rho\dot{y}\,|\dot{y}|$ the frictions, and $-\sum_{i=1}^{4}H_{yi}$ the hub force in the y axis[11].

The quadrotor system model can be rewritten in a state-space form

$$\dot{\boldsymbol{X}}=f(\boldsymbol{X},\boldsymbol{U}) \tag{3}$$

with $\boldsymbol{U}$ inputs vector and $\boldsymbol{X}$ state vector chosen as follows

$$\boldsymbol{U}=[U_1,U_2,U_3,U_4]^{\mathrm{T}}$$
$$\boldsymbol{X}=[\phi,\dot{\phi},\theta,\dot{\theta},\psi,\dot{\psi},z,\dot{z},x,\dot{x},y,\dot{y}]^{\mathrm{T}}$$

The transformation matrix between the rate of change of the orientation angles and the body angular rates can be considered as a unity matrix if the perturbations from hover flight are small. Then, we suppose that $\dot{\phi},\dot{\theta},\dot{\psi}\approx p,q,r$. U_1 is a control input for line movement on the z axis, U_2 a control input for roll movement, U_3 a control input for pitch movement, and U_4 a control input for yaw movement.

1.2 BEL algorithm model

Amygdala receives inputs from sensory input, orbitofrontal cortex and hypothalamus. There is one node for one stimulus, including the one only for thalamic stimulus. The thalamic connection is calculated as the maximum overall sensory input, and becomes another input to amygdala. For each node in amygdala, there is a plastic connection weight, also called learning weight. Any input signal is multiplied by this connection weight to provide the output of the node, such that

$$\begin{cases}A_i=S_iV_i, \quad i=1,2,\cdots,n\\ A_{n+1}=A_{\mathrm{th}}V_{n+1}, \quad A_{\mathrm{th}}=\max(S_i)\end{cases} \tag{4}$$

where A_i and V_i are the output and learning weight of the i-th node in amygdala, S_i the i-th sensory input, and A_{th} the hypothalamus output.

Orbitofrontal cortex is another important part of BEL model that makes a quick response to negative signal. The nodes behave analogously, with a connection weight applied to the input signal to create an output. Thus, the node output in orbitofrontal cortex can be given by

$$O_i=S_iW_i, \quad i=1,2,\cdots,n \tag{5}$$

where W_i is the learning weight of the i-th node in orbitofrontal cortex.

There is one output node for the BEL model, which is calculated by[4]

$$E=\sum\nolimits_{i=1}^{n+1}A_i-\sum\nolimits_{i=1}^{n}O_i \tag{6}$$

And likewise, there is another node that sums the outputs from nodes in amygdala except A_{th} and then subtracts from inhibitory outputs of the nodes in orbitofrontal cortex. The output of this node is calculated by

$$E'=\sum\nolimits_{i=1}^{n}A_i-\sum\nolimits_{i=1}^{n}O_i \tag{7}$$

The connection weights of the nodes in amygdala are adjusted proportionally to the difference between the emotional stress and the activation. The orbitofrontal cortex detects when expectations are not fulfilled and inhibits an improper emotional response. Hence, variations of the weights called as learning rules can be expressed by[4]

$$\begin{cases}\Delta V_i=\alpha_A S_i\max(0,\ R-A)\\ \Delta V_{n+1}=\alpha_A A_{\mathrm{th}}\max(0,\ R-A)\end{cases} \tag{8}$$

$$\Delta W_i=\alpha_O S_i(E'-R) \tag{9}$$

where α_A and α_O denote the learning rates in amygdala and orbitofrontal cortex, respectively. R denotes the reward signal, $i=1,2,\cdots,n$. They are constants used to adjust the learning speed.

2 Design for Flight Control System of Quadrotor Helicopter

2.1 Flight trajectory control loop design

According to the centroid kinematics equations of quadrotor unmanned helicopter, by neglecting some nonlinear property parts, we obtain a relationship between the centroid acceleration and the external force shown as

$$\ddot{x} \approx \frac{T_x}{m},\ \ddot{y} \approx \frac{T_y}{m},\ \ddot{z} + g \approx \frac{T_z}{m} \tag{10}$$

where T_x, T_y, T_z are the three components of lift force in ground axes, and

$$\begin{cases} T_x = T(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \\ T_y = T(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \\ T_z = T\cos\phi\cos\theta \end{cases} \tag{11}$$

From Eq. (11), we have

$$\begin{cases} \phi = \arcsin\left(\dfrac{T_x\sin\psi - T_y\cos\psi}{T}\right) \\ \theta = \arcsin\left(\dfrac{T_x - T\sin\phi\sin\psi}{T\cos\phi\cos\psi}\right) \end{cases} \tag{12}$$

where $T = \sqrt{T_x^2 + T_y^2 + T_z^2}$.

Therefore, an attitude estimator to get the control laws is designed as

$$\begin{cases} \phi_g = \arcsin\left(\dfrac{m\sin\psi_g U_x - m\cos\psi_g U_y}{T_g}\right) \\ \theta_g = \arcsin\left(\dfrac{mU_x - T_g\sin\phi_g\sin\psi_g}{T_g\cos\phi_g\cos\psi_g}\right) \end{cases} \tag{13}$$

where the co-controllers are designed by

$$U_x = K_x\ddot{x} = K_x(\dot{x}_d - \dot{x}) \tag{14}$$

$$U_y = K_y\ddot{y} = K_y(\dot{y}_d - \dot{y}) \tag{15}$$

$$T_g = \frac{T_z}{\cos\phi\cos\theta} = \frac{U_z + mg}{\cos\phi\cos\theta} \tag{16}$$

$$U_z = K_z\ddot{z} = K_{z1}\dot{z} + K_{z2}(z_d - z) \tag{17}$$

where K_x, K_y, K_{z1} and K_{z2} are the constant control gains.

2.2 Flight attitude control loop design

Adaptation and specialization are key properties of all biological organisms. Therefore, BEL model is used to design a flight attitude controller for quadrotor unmanned helicopter. We apply respectively four BEL algorithms in four control channels. BEL intelligent controller has some sensory inputs. One of the designer's tasks is to determine the sensory inputs. BEL intelligent controller has two states for each sensory inputs. One is amygdala output and another is orbitofrontal cortex output. Therefore the selection of sensory inputs is a key problem for BEL intelligent controller.

The height control law is designed as

$$U_1 = E_z(S_z, R_z, V_z, W_z) \tag{18}$$

$$S_z = \left[w_{z1}(z_d - z),\quad w_{z2}\frac{\mathrm{d}(z_d - z)}{\mathrm{d}t},\quad w_{z3}\int_z \mathrm{d}t \right] \tag{19}$$

$$R_z = w_{z1}\dot{z} + w_{z2}(z_d - z) + w_{z3}\int_z \mathrm{d}t \tag{20}$$

where $E_z(\cdot)$ is the output of BEL model for height control loop. w_{z1}, w_{z2} and w_{z3} are constant coefficients.

The rolling control law is designed as

$$U_2 = E_\phi(S_\phi, R_\phi, V_\phi, W_\phi) \tag{21}$$

$$S_\phi = \left[w_{\phi1}(\phi_d - \phi), w_{\phi2}\frac{\mathrm{d}(\phi_d - \phi)}{\mathrm{d}t}, w_{\phi3}\int(\phi_d - \phi)\mathrm{d}t \right] \tag{22}$$

$$R_\phi = w_{\phi1}(\phi_d - \phi) + w_{\phi2}\frac{\mathrm{d}(\phi_d - \phi)}{\mathrm{d}t} + w_{\phi3}\int(\phi_d - \phi)\mathrm{d}t \tag{23}$$

where $E_\phi(\cdot)$ is the output of BEL model for rolling control loop, here $A_{\mathrm{th}} = 0$, $w_{\phi1}$, $w_{\phi2}$ and $w_{\phi3}$ are constant coefficients.

The pitching control law is as follows

$$U_3 = E(S_\theta, R_\theta, V_\theta, W_\theta) \tag{24}$$

$$S_\theta = \left[w_{\theta1}(\theta_d - \theta),\ w_{\theta2}\frac{\mathrm{d}(\theta_d - \theta)}{\mathrm{d}t},\ w_{\theta3}\int(\theta_d - \theta)\mathrm{d}t \right] \tag{25}$$

$$R_\theta = w_{\theta1}(\theta_d - \theta) + w_{\theta2}\frac{\mathrm{d}(\theta_d - \theta)}{\mathrm{d}t} + w_{\theta3}\int(\theta_d - \theta)\mathrm{d}t \tag{26}$$

where $E_\theta(\cdot)$ is the output of BEL model for pitching control loop, here $A_{\mathrm{th}}=0$, $w_{\theta1}$, $w_{\theta2}$ and $w_{\theta3}$ are constant coefficients.

The yawing control law is designed as

$$U_4 = E(S_\psi, R_\psi, V_\psi, W_\psi) \tag{27}$$

$$S_\psi = \left[w_{\psi1}(\psi_d - \psi),\ w_{\psi2}\frac{\mathrm{d}(\psi_d - \psi)}{\mathrm{d}t},\ w_{\psi3}\int(\psi_d - \psi)\mathrm{d}t \right] \tag{28}$$

$$R_\psi = w_{\psi1}(\psi_d - \psi) + w_{\psi2}\frac{\mathrm{d}(\psi_d - \psi)}{\mathrm{d}t} + w_{\psi3}\int(\psi_d - \psi)\mathrm{d}t \tag{29}$$

where $E_\psi(\cdot)$ is the output of BEL model for yawing control loop, here $A_{\mathrm{th}} = 0$. $w_{\psi1}$, $w_{\psi2}$ and $w_{\psi3}$ are constant coefficients.

2.3 Flight control system structure

According to the designed trajectory controller and attitude controller, a flight control system of quadrotor unmanned helicopter is established in Fig. 1. For the quadrotor unmanned helicopter, the difficulty of designing the control system is that the movements on x-axis and y-axis are under-actuated, which are controlled by pitching angle and rolling angle respectively. The trajectory controller is divided as two parts: co-controller and attitude estimator. The former is designed by Eqs. (14—17), and the latter by Eq. (13). The attitude controller is expressed using Eqs. (18—29).

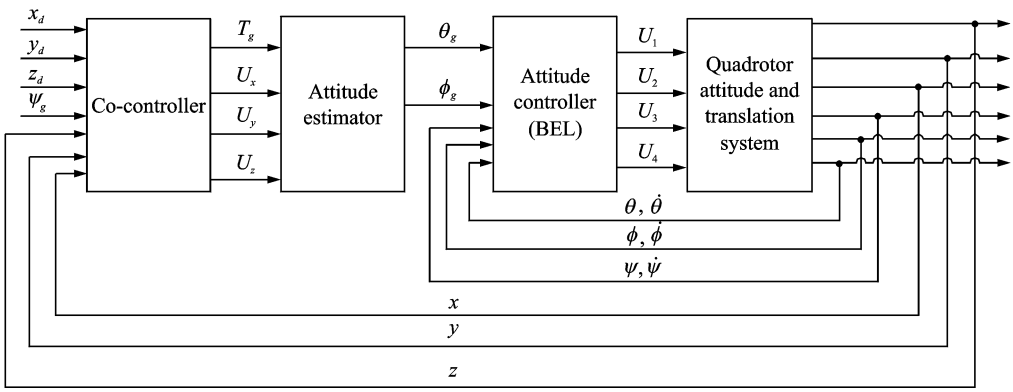

Fig. 1 BEL-based intelligent flight control system for quadrotor helicopter

3 Simulation Analysis

The simulations of two control techniques are presented, including the traditional control scheme and the BEL intelligent control scheme for the flight control of a quadrotor unmanned helicopter. Both of them have the same trajectory controllers but different attitude controllers. The traditional attitude controller adopts proportional-integral-derivative (PID) scheme, the control gains of which are same with constant coefficients w in BEL controller. The nonlinear model of the quadrotor unmanned helicopter is given by Eqs. (1—3).

Figs. 2—4 show the height movement, x-axis movement and y-axis movement responses under the two different control schemes, respec tively . In the response curves , the closed-loop system performance using BEL intelligent controller is compared with that of traditional controller. In simulation results, BEL intelligent controller can settle faster with less distortion. The learning capability of BEL can also bring about several advantages, such as robustness against noise and model uncertainties, if the learning parameters are well tuned.

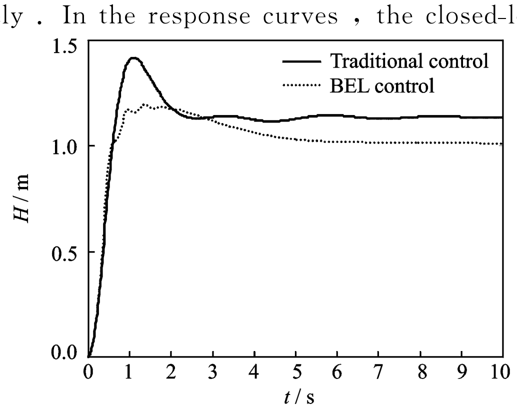

Fig. 2 Height control responses

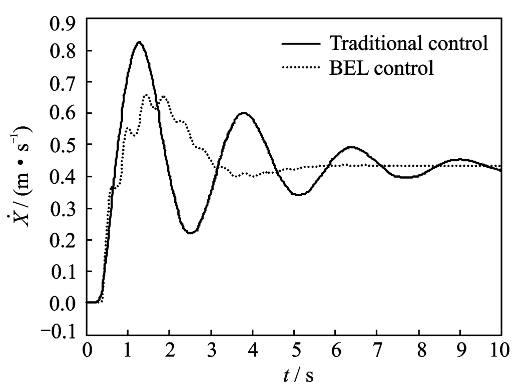

Fig. 3 Movement responses on x-axis

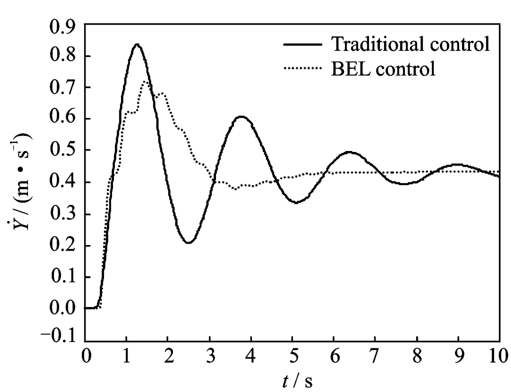

Fig. 4 Movement responses on y-axis

4 Conclusions

A novel flight control system for quadrotor unmanned helicopter is investigated, in which a co-controller and a state estimator are developed in trajectory control loop, and a BEL intelligent controller based on brain emotional processes in limbic system is applied to the attitude control loop. The performance of the BEL-based closed-loop control system of quadrotor unmanned helicopter is compared with that of the traditional controller. Simulation results exhibit that the BEL intelligent flight control system is superior to the traditional one in terms of control characteristics such as response and accuracy.

In all, the BEL intelligent control is a reliable and effective control method, and is simple in implementation and flexible in high performance applications. Fast auto learning and high control potency of BEL intelligent control promise more real engineering applications. By choosing the sensory input signals, the BEL intelligent control method enables the designer to shape the response in accordance with the multiple objectives of choices. However, the convergence of the BEL algorithm and the stability of BEL-based control system need to be further studied in future.

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