Direct Inverse Control Based on Neural Network for Unmanned Small Helicopter Attitude and Altitude Control

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***Abstract*—This paper describes the development of inner loop control of a small helicopter using artificial neural network. A Direct Inverse Control (DIC) based on Neural Network is proposed to maintain the attitude (roll, pitch, and yaw) position on the helicopter hovering state, for several different altitude values. The adopted neural networks learning method to train the network is the backpropagation algorithm. Simulations using real experimental helicopter hovering flight data were conducted to verify the performance of the proposed NN-DIC system. It was revealed that the simulated NN-DIC system can follow the hovering trajectory reference with very low error values.**

***Index Terms*—DIC; Unmanned Small Helicopter; Neural Network; Invers Model.**

I. INTRODUCTION

Helicopter is categorized as one of the unmanned aerial vehicles (UAVs) that have the ability to hover. Some significant advantages of helicopter compared to other conventional fixed-wing platforms are the ability to take off and land vertically and the possibility to fly in low speed and at low altitude. The second capability makes it easy to reach dangerous and narrow terrain, so that it is commonly preferred for various applications such as target tracking, searching, rescuing, surveillance, reconnaissance, and remote monitoring [1]. In this paper, small helicopter is of a particular interest because it comes with various advantages compared with the larger counterparts. Some obvious superiority are the smaller size, lighter weight, and lower development cost.

The main challenge to design a stable control system for a small helicopter is the fact that this plant is a complex MIMO system that is under actuated, highly coupled and typically unstable [2,3]. Recent published works have reported that the commonly used methods to design the control system of a small helicopter can be divided into linear and the non-linear approaches. Some examples of the linear control approaches are the classical proportional integral derivative (PID) [4,5], LQG [6], and the H-Infinity control [7,8]. Meanwhile, some non-linear control methods are the feedback linearization [3], the dynamic inversion [9,10], the sliding mode control technique [11], and the Artificial Neural-Network (ANN) based controller [12-15]. Among all of the aforementioned non-linear control method, ANN-based controller is the most promising approach since there are no mathematical simplifications required in modelling the plant.

Former studies on utilizing backpropagation based controller under the optimized Direct Inverse Control (DIC) scheme have been reported for controlling the unmanned small helicopter [17]. However, previous research work on small helicopter was only focusing on a certain attitude and altitude value. In this paper, an enhanced ANN-based controller that is able to control the small helicopter in its hovering mode at various altitude values is proposed.

This paper is organized in five sections. The section after this introduction section explains the small helicopter, including the experimental data acquisition. The proposed neural network control algorithm is discussed in Section III. Then, the justification of the proposed ANN-based controller through simulation on the experimental data is elaborated in Section IV. Section V summarizes the paper.

II. THE SMALL HELICOPTER

A. Small Helicopter Model

The movement of an unmanned small helicopter is controlled by four input control parameters: longitudinal cyclic pitch, lateral cyclic pitch, collective pitch tail rotor and main rotor collective pitch (*δ_lon,δ_lat,δ_ped ,δ_col*) [18]. The expected output is the helicopter motion dynamics which can be divided into two movements, namely the linear movement and the attitude movement during flight. Its response consists of the attitude angle vector [*∅,θ,φ*], the linear velocity vector [*u*,*v*,*w*], the position vector [*x*,*y*,*z*], the angular velocity vector [*p*,*q*,*r*] and the derivative vector of position [*vz*,*vy*,*vx*] on the body coordinate. The equations of motion of a small helicopter model can be expressed as follows:

$$\begin{cases} \dot{u} = vr - wq - g\sin\theta + (X_{mr} + X_{fus})/m \\ \dot{v} = wp - ur - g\sin\phi\cos\theta + (Y_{mr} + Y_{fus} + Y_{tr} + Y_{vf})/m \\ \dot{w} = uq - vp - g\cos\phi\cos\theta + (Z_{mr} + Z_{fus} + Z_{ht})/m \\ \dot{p} = qr(I_{yy} + I_{zz})/I_{xx} + (L_{mr} + L_{vf} + L_{tr})/I_{xx} \\ \dot{q} = pr(I_{zz} - I_{xx})/I_{yy} + (M_{mr} + M_{hf})/I_{yy} \\ \dot{r} = pq(I_{xx} - I_{yy})/I_{zz} + (Q_{mr} + N_{vf} + N_{tr})/I_{zz} \\ \dot{\phi} = p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\ \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{\varphi} = q\sin\phi/\cos\theta + r\cos\phi/\cos\theta \end{cases} \tag{1}$$

From the equations above, the small helicopter system can be considered as a lumped model which consists of a main rotor (mr), a tail rotor (tr), a horizontal stabilizer (hf), a vertical stabilizer (vf) and a fuselage. X, Y and Z are the components of the resultant force of the thrusts generated by the main and tail rotors, damping forces from the horizontal and vertical stabilizer, and also the aerodynamic force due to fuselage. L, M and N are the moments, which are produced by all forces. The force on the main rotor can be described as:

$$T_{mr} = C_{Tmr}\rho(\Omega R)^2 \pi R^2 \tag{2}$$

where C_{Tmr} is the main rotor thrust coefficient, ρ is the air density, Ω is the main rotor speed, and R is the main rotor radius. The main rotor thrust coefficient, C_{Tmr}, can be calculated using the following equation:

$$C_{Tmr} = 0.5a_0\left(\theta_0\left(\frac{1}{3}+\frac{\mu^2}{2}\right)+\left(\frac{\lambda-\lambda_0}{2}\right)\right) \tag{3}$$

The lift forces produced by the main rotor on the body coordinate can be written as follows:

$$\begin{cases} X_{mr} = -T_{mr}a \\ Y_{mr} = T_{mr}b \\ Z_{mr} = -T_{mr} \end{cases} \tag{4}$$

Meanwhile, the pitch and roll moments can be expressed as:

$$\begin{cases} L_{mr} = \left(K_\beta + T_{mr} * h_{mr}\right)b \\ M_{mr} = \left(K_\beta + T_{mr} * h_{mr}\right)a \end{cases} \tag{5}$$

Variables a and b in Eq. (4) are the flapping degree, whereas K_β and h_{mr} in Eq. (5) are the hub torsional coefficient and the main rotor hub height from the center of gravity, respectively. The flapping angles are assumed as:

$$\begin{cases} a = -\delta_{lon} \\ b = \delta_{lat} \end{cases} \tag{6}$$

The tail collective pitch mainly controls the helicopter direction, and the collective pitch of main rotor commands its height. Finally, the two inputs are approximated by:

$$\begin{cases} \delta_{col} = {T_{mr}}/{C_{mr}} \\ \delta_{ped} = {T_{tr}}/{C_{tr}} \end{cases} \tag{7}$$

All of the equations above show that the small helicopter is very difficult to be modelled mathematically due to the existence of various plant-specific parameters. Generally, the approximation values of all of these parameters are obtained by conducting an accurate, precise, and complex experiment which requires a very high cost and consumes a considerably long time.

B. Small Helicopter Platform

This research utilized a TREX 450 R/C. The main components of the helicopter are 3 digital servos to direct the main rotor collective pitch, one digital servo to direct the tail collective pitch and also one Brushless Motor (1800KV) driven by a 45A brushless Electronic Speed Controller (ESC). The main power was obtained from a 1400mAh Li-Po battery. The avionic system to collect the experimental data consists of a microcontroller AT Mega 2560, a Global Position System (GPS), a digital compass chip HMC 5883L, a 6 DOF accelerometer, a Gyro MPU-6000 and a barometric pressure sensor. The three last sensors were integrated in an Inertial Measurement Unit (IMU) system.

To control the helicopter, 5 input signals were required. These input signals are: 3 PWM signals to control the main blades, 1 PWM signal to control the BLDC servo, and 1 PWM signal to control the tail blade servo. Meanwhile, the expected outputs for the hovering mode are the helicopter motion dynamics which consist of the attitude angle vector [∅,θ,φ] and the altitude. In this hovering mode, the changes of x and y position were near zero so that these values can be neglected.

For the purpose of the experimental data acquisition, the unmanned small helicopter was controlled by a human pilot using a Radio Control to keep the helicopter in its hovering state but in several different altitude values. The data were collected twice, one for the ANN training and the other for the ANN testing. The utilized sampling time was 200 ms. The helicopter inputs are depicted in Figure 1 and 2, whereas the outputs are shown in Figure 3.

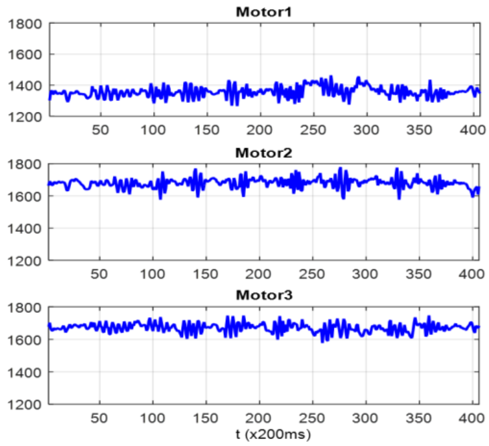


Figure 1: PWM signals of the three main blade servos

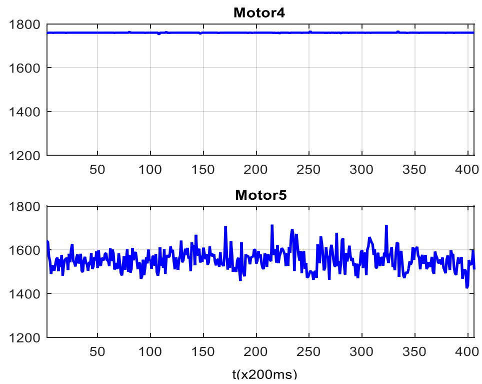


Figure 2: PWM signals of the BLDC and the tail blade servo

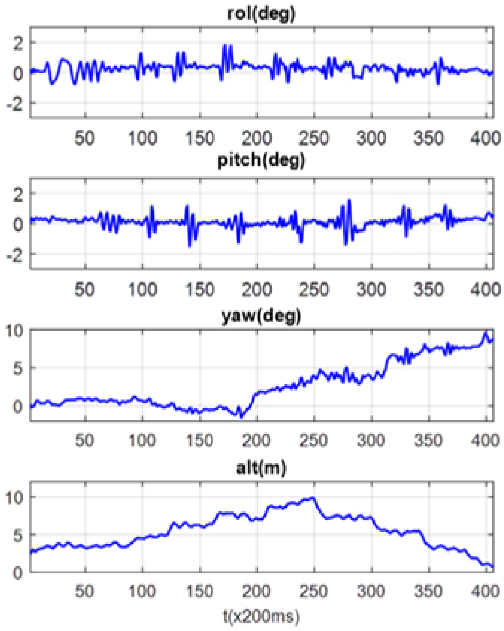


Figure 3: The attitude and altitude data

III. THE PROPOSED CONTROL SYSTEM

A. General Control Strategy

The general control system of an autonomous unmanned small helicopter is depicted in Figure 4. The control system can be divided into the inner loop control and the outer loop control. The outer loop control provides the attitude degree reference to the inner loop control based on its position reference [18]. This research focuses on the inner loop ANN-based controller for controlling the helicopter height during its hovering state.

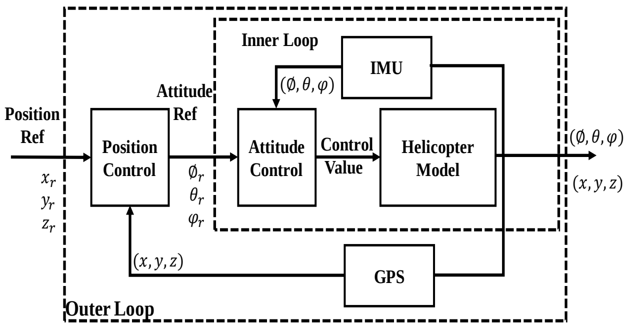


Figure 4: The block diagram of a general control system of a helicopter

B. The Proposed ANN-Based Direct Inverse Control

Direct inverse control based on artificial neural network (NN-DIC) is a simple and straightforward neural network control technique which utilizes the nonlinear plant inverse model [16]. NN-DIC system consists of an inverse controller that is directly connected to the controlled plant as depicted in Figure 5. In this research, the small helicopter plant was replaced by an ANN-based identification system to model the plant. The ANN learning methodology adopted for both the inverse controller and the plant identification is the backpropagation learning algorithm.

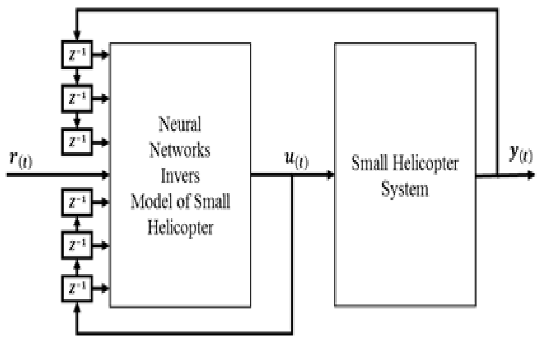
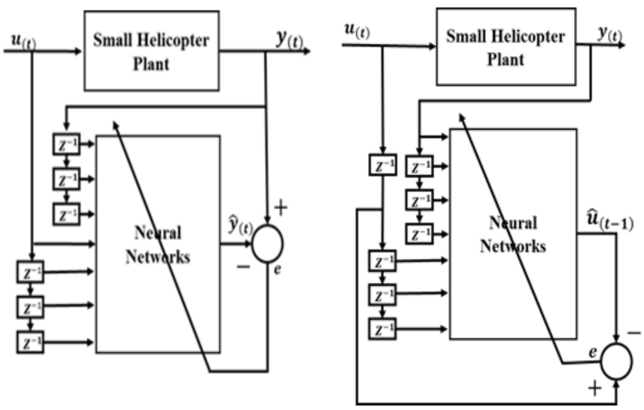


Figure 5: Neural Networks Direct Inverse Control (NN-DIC)

The block diagram of the neural network training for both the inverse controller and the plant identification are shown in Figure 6 (a) and (b), respectively. For the inverse controller training, backpropagation learning algorithm was adopted to train the pre-configured neural network with 31 input neurons, 40 hidden neurons and 5 output neurons. Similar training mechanism was also adopted for the plant identification which utilizes a neural network configuration of 32 input neurons, 35 hidden neurons and 4 output neurons. As can be seen from Fig. 6, the two ANN-architectures utilize 3 delays for each data.

For the neural network training, 400 samples of experimental data as shown in Figure 1 – 3 were utilized. Backpropagation learning algorithm was adopted with 0.1 learning rate and without using momentum. The plant identification training requires 10,000 epochs to produce a training Mean Sum Square Error (MSSE) value of 0.00107. On the other hand, the inverse controller training requires 8,000 epochs to produce a training MSSE of 0.0019.



(a) Inverse controller (b) Identification system

Figure 6: ANN-based training mechanisms

IV. SIMULATION RESULTS AND DISCUSSION

The optimum weights obtained from the neural network training were then tested under the NN-DIC system, using a different data set, which has a steadier altitude degree compared with the training data set. The simulation results of the proposed NN-DIC system for attitude and altitude are depicted in Figure 7 and 8, respectively.

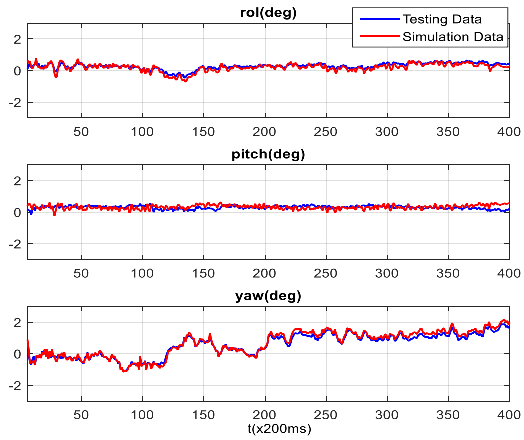


Figure 7: Response result of attitude

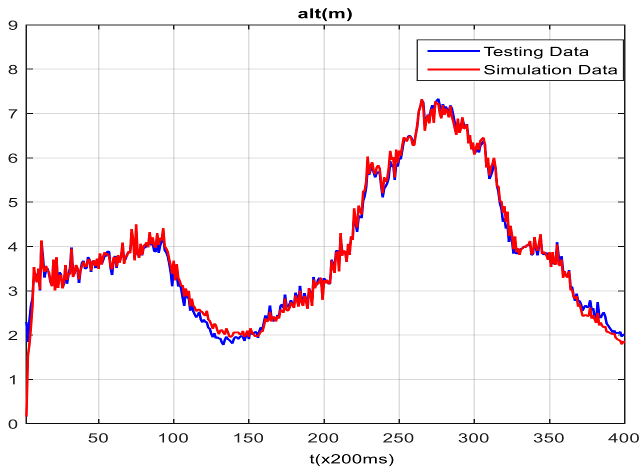


Figure 8: Response result of altitude

Figure 7 shows that the attitude signals of the simulated NN-DIC system can resemble the given reference signal (testing data) with only some slight discrepancies. The Mean Sum Square Error (MSSE) value for the attitude is 0.0273 degree, where the Mean Square Error (MSE) for roll is 0.0127 degree, MSE for pitch is 0.022, and MSE for yaw is 0.0473. These values indicate that the error values are still within the acceptable error range of below 0.05 degree.

Meanwhile, the altitude response of the simulated NN-DIC system in Figure 8 also reflects that the output signal (simulation data) is almost identical to the reference signal (testing data). The MSE of altitude data in this simulation is 0.01384 meter. This very low error value further indicates that the performance of the proposed NN-DIC system is very appropriate to be used as the controller of a small helicopter.

V. Conclusions

Verification of the ability of the proposed NN-DIC system as the inner loop controller of a small helicopter has been conducted through simulations using real experimental data at various altitude values during hover state. The low error values of the simulation results have proven that the proposed backpropagation NN-DIC system can be adopted for the small helicopter inner loop controller at hovering state. An obvious advantage of the proposed NN-controller system compared to other conventional analytical controllers is that the NN-controller does not require any complicated mathematical model.

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