Optimized Neural Network-Direct Inverse Control for Attitude Control of Heavy-Lift Hexacopter

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***Abstract*—This paper discusses a neural network based on direct inverse control (DIC) to control the roll, pitch, and yaw in maintaining the hovering condition of a heavy-lift hexacopter. To improve the control of the hexacopter, the authors propose a DIC-optimized method of retraining the inverse model using new data collected from optimal motions of the hexacopter generated by the desired input. The experiment showed that both the DIC model and the DIC-optimized model had good performances with small MSSE values; however, the latter was more effective than the former.**

***Index Terms*—DIC; Heavy-Lift Hexacopter; Neural Network; Optimized DIC.**

I. INTRODUCTION

Hexacopter is classified as one of the unmanned aerial vehicles (UAVs) within the rotary-wing group classification. The rotary wing vehicles are the most favored types of UAV due to numerous reasons, such as, their ability to hover and perform vertical take-offs and landings (VTOLs) that do not require a long runway facilities and their ability to undertake exceptional maneuvers [1].

Hexacopters use six rotors with its propellers that are placed on either side of a rigid body frame. Therefore, they are able to lift heavier payloads, perform better maneuvers and have a better stability level compared with the quadcopter. However, the additional numbers of rotors cause additional complications to the hexacopter. As it is well known, the hexacopter has a characteristic of a nonlinear system, including the problem of a coupling and parametric uncertainty. As a consequence, the control state for a stable flight performance of the hexacopter is more challenging.

Numerous studies have been conducted to solve the hexacopter control issues, such as using a Proportional Integral Derivative (PID) [1, 2], an input-output feedback linearization [3], and a back-stepping control algorithm [4]. However, these control systems are not suitable for the nonlinear system of the hexacopter system, showing a lower performance in terms of robustness and less adaptive to the environment and parameter variations due to outside disturbance.

Another control method that might be used for hexacopter is the neural network (NN) [5, 6]; however, as far as we know, the development of the neural networks based control system for a hexacopter or another rotor based UAVs is still in the simulation stage. This paper discusses the design of a control system for a hexacopter movement, especially, the hovering ability. The proposed control system for the hexacopter is a neural network based on a direct inverse control (DIC) scheme because neural networks is proven to be able to model any nonlinear systems using its learning mechanism, and it has the ability to adaptively follow to the changing environment of the utilized plants. The learning of the neural networks is accomplished by using the real flight-data taken from experiments that only focus on the hovering movement.

This paper consists of the following sections: Section II explains the dynamic model of the heavy-lift hexacopter, while Section III discusses the development of the neural networks based control system under DIC scheme method. The experimental results and its analysis of the proposed controller's output response are discussed in Section IV. The conclusion is given in Section V.

II. DYNAMIC MODELING OF THE HEAVY-LIFT HEXACOPTER

The heavy-lift hexacopter is moved, in simple terms, by six rotors placed at the end of the frame. The structure and frame of a hexacopter are shown in Figure 1 as follows:

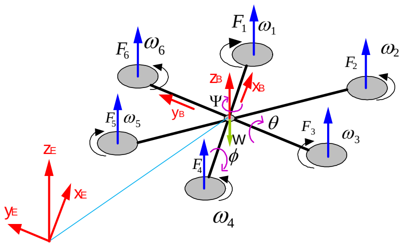


Figure 1: Structure and frames of hexacopter

As can be seen from this figure, the description of the hexacopter's movement uses two references, namely the inertia of the earth frame (E-frame) and the body frame (B-frame). It can also be clearly seen that the three Euler angles, the yaw angle ψ, pitch angle θ, and roll angle φ, forming a vector $\eta = [\varphi, \theta, \psi]^T$, which constitute the orientation of the hexacopter's movement. Vector $\xi = [x, y, z]^T$ is the frame inertia taken from the position of the hexacopter. As a consequence, the transformation between the angle velocity and the position of the body fixed into the inertia frame, can be calculated through a matrix R as follows:

$$R = \begin{bmatrix} \cos\theta\cos\psi & \cos\psi\sin\theta\sin\phi - \cos\phi\sin\psi & \cos\phi\cos\psi\sin\theta + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\theta\sin\phi\sin\psi & \cos\phi\sin\psi\sin\theta - \cos\psi\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \quad (1)$$

The movement of the hexacopter, in essence, depends on the gravity and the thrust from the rotors, but the influence of the drag rotor and the air friction also play an important role, which makes the mathematical model of the hexacopter more difficult. In addition, there are various parameters that influence the aerodynamic of the hexacopter, which should be considered, such as the propeller rotation, propeller velocity changes which resulting additional torque, and the gyroscope effect caused by the direction changes from the hexacopter. Considering the hexacopter is assumed to have a rigid body and symmetrical structure and using the Newton-Euler formula, the dynamic model of the hexacopter can be derived as below:

$$\begin{cases} \ddot{X} = -(\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)\dfrac{u_1}{m} \\ \ddot{Y} = (-\cos\phi\sin\theta\sin\psi - \cos\psi\sin\phi)\dfrac{u_1}{m} \\ \ddot{Z} = -g + (\cos\theta\cos\phi)\dfrac{u_1}{m} \\ \ddot{\phi} = (\dot{\theta}\dot{\psi}(I_{yy} - I_{zz}) + \tau_x) / I_{xx} \\ \ddot{\theta} = (\dot{\phi}\dot{\psi}(I_{zz} - I_{xx}) + \tau_{yy}) / I_{yy} \\ \ddot{\psi} = (\dot{\phi}\dot{\theta}(I_{xx} - I_{yy}) + \tau_z) / I_{zz} \end{cases} \tag{2}$$

and the relationship between the base movement and the propeller velocity can be seen in the following equation:

$$\begin{cases} U_1 = b\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2 + \omega_5^2 + \omega_6^2\right) \\ U_2 = l\,b\left(-\omega_2^2 - \omega_3^2 + \omega_5^2 + \omega_6^2\right) \\ U_3 = l\,b\left(-\omega_1^2 - \omega_2^2 - \omega_6^2 + \omega_3^2 + \omega_4^2 + \omega_5^2\right) \\ U_4 = d\left(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2 - \omega_5^2 + \omega_6^2\right) \\ \omega = -\omega_1 + \omega_2 - \omega_3 + \omega_4 - \omega_5 + \omega_6 \end{cases} \tag{3}$$

in which, $\ddot{X}, \ddot{Y}, \ddot{Z}$ are the hexacopter linear acceleration with respect to E, $\ddot{\phi}, \ddot{\theta}, \ddot{\psi}$ are the hexacopter angular acceleration with respect to B, m is the mass of the hexacopter, g is the acceleration due to gravity, I_{XX}, I_{YY}, I_{ZZ} are the body moment of inertia around the *xyz*-axis, U_1 is the vertical thrust, U_2 is the roll torque, U_3 is the pitch torque, U_4 is the yaw torque, ω_n is the propeller speed, b is the thrust factor, d is the drag factor, and l is the distance between the center of hexacopter and the center of the propeller.

Based on these equations, it can be seen that the input of the hexacopter model is the rotor rotation velocity, while the output is the attitude angle of the hexacopter, i.e., the roll, the pitch, and the yaw and the altitude. To demonstrate this in more detail, the hexacopter movement control system can be depicted in a block diagram as shown in Figure 2:

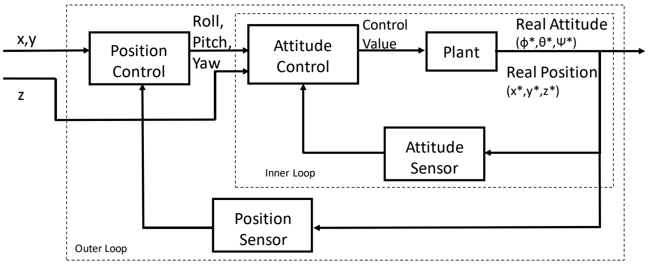


Figure 2: Block diagram of hexacopter control system

As can be seen in Figure 2, the altitude control system, which acts to control the roll (φ), the pitch (θ), and the yaw (ψ) of the hexacopter that has to be the same as the input reference, is known as the inner-control loop. Meanwhile, the position control, which is the movement control in the vertical plane of the z-axis (altitude control) and in the horizontal plane in the xy-axis, is called the outer-control loop. In this paper, the main focus of the research is to control the hovering movement characteristics by maintaining the distance between the height of the hexacopter and the ground, hence this paper only considered with the inner-control loop only.

The hexacopter used in this research has a frame length of 2.4 m, with the total thrust in each motor is 12.34 kg. The main components of the hexacopter are six units of the Electronic Speed Controller T-Flame 80 A, six units of BLDC T-Motor U11 100 KV motors, six pieces of Propeller Carbon Fiber Xoar 28” x 8”, one unit of microcontroller, Compass, and GPS sensors. This hexacopter is also equipped with an inertial measurement unit (IMU) that consists of a gyroscope, an accelerometer and a barometer, one unit of radio control, a voltage regulator and four Li-Po 12S 10,000 mAh batteries.

III. NEURAL NETWORKS BASED ON DIRECT INVERSE CONTROL (DIC)

A control system to be used for a nonlinear characteristic of any plant is very difficult to accomplish; hence, it requires extensive system knowledge and a rather complicated mathematical model. One of the most widely used methods to overcome this problem is a neural network based inverse control system scheme, in which the neural network has the ability to model any nonlinear system.

A neural network is one of the most accurate means of identifying a dynamic system that has nonlinear characteristics [7]. Direct inverse control (DIC) scheme, is a simple system that includes neural networks as the core of the control system and another neural networks performing the system identification of the plant7. DIC scheme, then, is a cascade system of the inverse model of the plant as the control system and system identification that mimick the plant behavior. The block diagram of the NN-DIC system is presented in Figure 3.

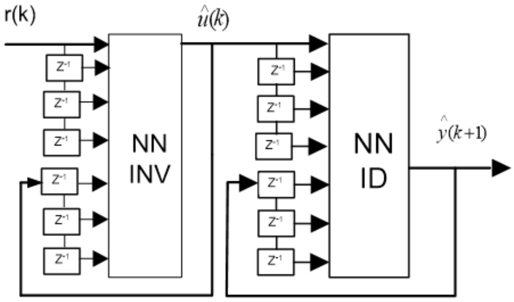


Figure 3: Block diagram of DIC

Both the neural networks based inverse controller and system identification are then trained by using the experimental data acquired from the heavy-lift hexacopter.

An identification model for a non-linear system with input x and output y can be described as:

$$y(k) = f(\varphi(k), \theta) \tag{4}$$

where y(k) is the output model, φ(k) is the regression vector, θ is the parameter vector, and f is the function, which represents the mapping function between y(k), φ(k) and θ.

Based on the structure of the nonlinear autoregressive with exogenous (NARX) model, the regression vector can be determined by the number of prior input and output as follows:

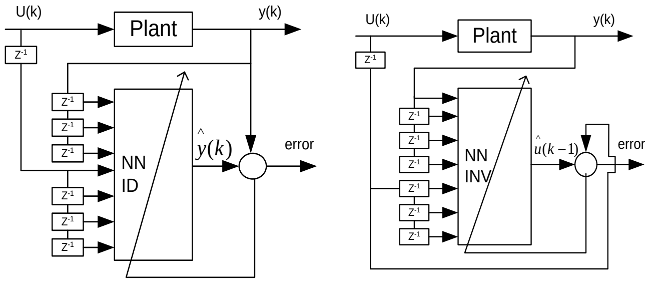
$$\varphi(k) = (y(k-1), .., y(k-N_y), x(k-1), .. x(k-N_x)) \tag{5}$$

where Ny and Nx are the numbers of output and input memory which correspond to the delay of the output and input data in the model, respectively.

Having explained the identification model for a non-linear system, the inverse controller model is basically the reverse of the plant identification model, which can be described by the following equation:

$$x(k) = f\left(x(k-1), ., x(k-N_x), y(k+1), . y(k-N_y)\right) \tag{6}$$

In this experiment, the chosen number of delay for both the input and output data, N_x and N_y is 2. A block diagram of the identification system and inverse model can be seen in Figure 4, where the neural network configuration for the identification system has 26 input neurons, hidden layer with 35 neurons, output layer with 4 neurons and that for the inverse control system is 24 input neurons, 35 hidden neurons, 6 output neurons.



(a) (b)

Figure 4: the block diagram of a) identification system, b) Inverse model

Based on the hexacopter model as described in Equation (2) and (3), the plant input $x(k)$ consists of the six motor speeds (PWM#1 to PWM#6), while the plant output $y(k)$ consists of the dynamics of the roll, pitch, yaw, and altitude movements.

The optimized DIC method was conducted to improve the performance of DIC in terms of the characteristics of the dynamical system, such as a low margin of error, fast settling time, and stable responses [8]. The first step was performed by assigning a set point value to the DIC model. This step produces new data of the dynamic system and motor speed. After that, the training to the inverse model was carried out again using the new data. The weights obtained from this training were then used for the optimized DIC system.

IV. EXPERIMENTAL RESULTS

In this research, data acquisition was conducted by moving the heavy-lift hexacopter on a hovering state using a testbed. The data were acquired twice, one as the training data and the other as the testing data. Identification system and the inverse model training were then performed using the back propagation learning algorithm.

The identification training converged after *74,925* epoch, resulting a training Mean Sum Square Error (MSSE) of *4.129 x* 10^{-5}. The identification testing showed a MSSE value of *8.2618 x* 10^{-4}. The outcome of the identification test showed good results in which the output response is able to follow the reference data. Meanwhile, the inverse model training converged after *37,741* epoch and the training MSSE value was *3.83 x* 10^{-2}. The inverse model test produced a MSSE value of *6.68 x* 10^{-2}. This low error value reflects that the inverse model training has succeeded in modeling the inverse of the heavy-lift hexacopter.

The weights obtained from the identification and inverse model training were then utilized for the NN-based DIC system. The testing results of the DIC are depicted in Figure 5.

From Figure 5, it can be seen that the responses of DIC can follow the given test data and produce a MSSE value of *0.0014*, although there are 1.71° of discrepancy in the pitch data. Maximum error occurs due to the significant movement shift when the hexacopter is performing a dramatic inverse movement.

To comprehend the details of the errors, the response of each movement can be analyzed using the standard deviation which states the maximum error limit of the data. The produced errors are considered to be acceptable if their values are below the corresponding standard deviation. The standard deviation of error can be obtained using the following equation:

$$s = \sqrt{\frac{\sum_{i=1}^{1}\left(e_{rr_i} - \overline{e_{rr}}\right)^2}{n-1}} \tag{7}$$

in which s is the standard deviation, $\overline{err}$ is the mean error, err is the error, and n is the total data. Using Equation (7), the standard deviations of the error for roll, pitch, yaw and altitude movements are *4.004°*, *6.228°*, *2.076°* and *0.186* centimeters, respectively.

The error values for roll, pitch, yaw and altitude movements can be seen in Figure 6, and 7 respectively. Based on the error values in Figure 6(a), the maximum error for roll movement is *3.373°*. This value is still below the error standard deviation of *4.004°*. Therefore, it remains within the acceptable limit. Regarding the pitch movement, as seen in Figure 6(b), the maximum error is 5.*426°* and the standard deviation is *6.228°*. In terms of the yaw movement, as seen in Figure 7(a), the maximum error is *1.683°* while the standard deviation is *2.076°*. Thus, all the occurred errors for pitch and yaw movements are still within the acceptable limit.

The hovering movement is the movement of the hexacopter at a certain height in which the position is certain, or where it can be said that the hexacopter is in a fixed z-axis or altitude. In relation to this, the highest error of altitude in Figure 7(b) of *0.006567* centimeters can be considered as a very small error. In other words, the hexacopter has succeeded in maintaining its altitude. Furthermore, this maximum error value is far below its error standard deviation of *0.186* centimeters. Overall, the error values in every movement are still within the acceptable range.

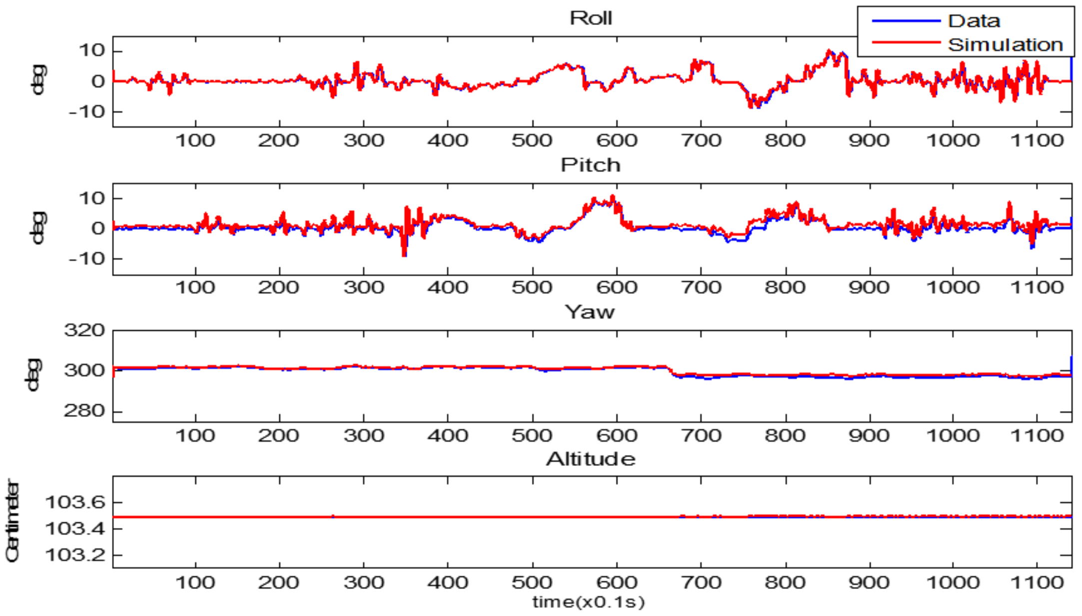
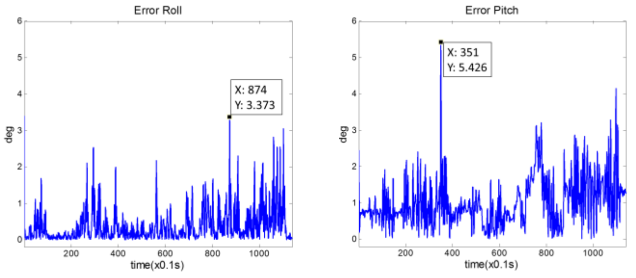
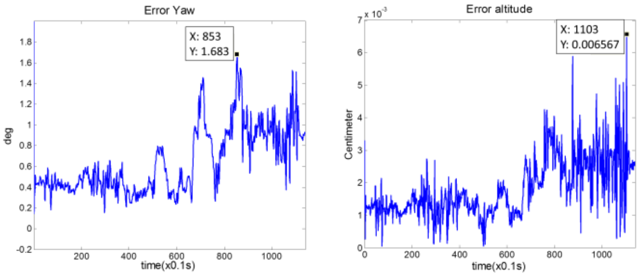


Figure 5: DIC response test result



(a) (b)

Figure 6: Error graphs test result at (a) Roll dan (b) Pitch movement



(a) (b)

Figure 7: Error graphs test result at (a) Yaw movement and (b) Altitude

For the optimized DIC, the generated set point data were roll = 0°, pitch = 0°, yaw = 299°, and altitude = 1,035 m. This data were then utilized to retrain the inverse model of the hexacopter. Optimized DIC system was built using the obtained weight, and the comparison of the testing result for the optimized and unoptimized DIC is depicted in Figure 8.

Figure 8 shows that the responses of the optimized DIC were better than those of the unoptimized DIC. The MSSE value of the former was 8,6 x 10^{-5}, while that of the latter was 1,72 x 10^{-3}. A more comprehensive comparison of both methods is given in Table 1.

Table 1 shows that the errors in roll, pitch, and yaw movements in the optimized DIC were smaller than those in the unoptimized DIC. However, the settling time of the optimized DIC was slower than that of the unoptimized DIC due to the existence of small oscillations causing longer time to reach its stable state.

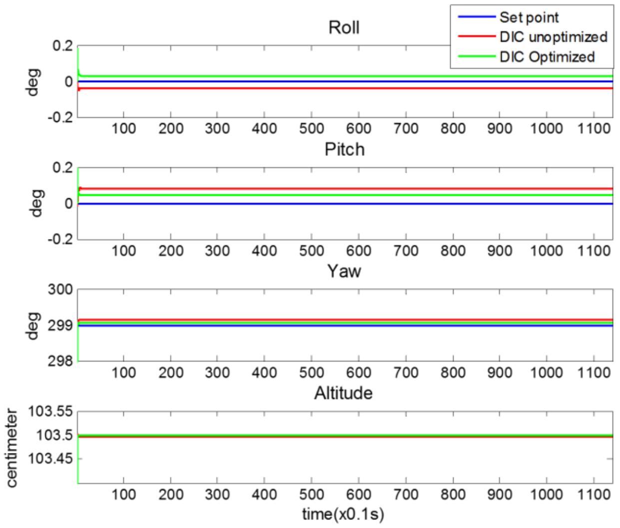


Figure 8: Comparison of the Optimized and the Unoptimized DIC Testing

Table 1
Comparison between Optimized DIC Model and Unoptimized DIC Model during hovering

Model	MSSE roll	MSSE pitch	MSSE yaw	Settling time
Unoptimized DIC	0.0418	0.0824	0.15	11 s
Optimized DIC	0.0287	0.0467	0.06	13 s

V. CONCLUSION

This paper showed that the heavy-lift hexacopter was able to maintain a hovering condition using NN-DIC. The error values in every movement, which consist of roll, pitch, yaw and altitude, are still within the acceptable range. The optimized DIC method showed better performance than the unoptimized DIC in terms of smaller errors; however, the settling time of optimized DIC was slower than that of the unoptimized DIC. The maneuver control of the heavy-lift hexacopter will be developed in the future.

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